ABSTRACT

A LABORATORY AND FIELD STUDY OF THE ATTENUATION OF SOUND INTENSITY USING A WHISTLE AS THE SONIC GENERATOR

by
Navneet Kumar

This study investigated the attenuation of sound intensity using a whistle as the sonic generator along with the detailed analysis of all the previous studies. Attenuation of sound in air studies were performed in Otto H. York Center for Environmental Engineering and Science at New Jersey Institute of Technology. Sound attenuation through air was measured by doubling the distance for each of five whistles. It was concluded that Whistle No.5 gives the highest sound intensity of 140.54 dB at a distance of 0.75 ft , the closest distance used for measurement, at a air flow rate of 7.5 SCFM. These data were extrapolated to within one-inch of the whistle and the sound intensity at this distance was about an average of 160.7 dB. The data of sound intensity in decibels versus distance in feet were curve fit using the best-fit curve, Power Equation. It was also concluded that a single whistle produces high sound intensities in comparison to the combination of two whistles.This study investigates the recommendations of previous studies for re-conducting the attenuation of sound focused in an artificial fracture. Previous studies by Zarnetske and Godde recommended that the Bootwala, 2000 field study should be re-conducted with the position of the microphone directed into the fracture using Whistle No. 5. This study has developed the complete procedure and methodology to conduct the above studies in the field. Previous studies should be expanded to give more knowledge from controlled laboratory tests. The work should be expanded to include soil, in addition, to the porous rock slab

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APPROVAL PAGE

A LABORATORY AND FIELD STUDY OF THE ATTENUATION OF SOUND INTENSITY USING A WHISTLE AS THE SONIC GENERATOR

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Dedicated to my beloved parents, sister and my cousin Soni.

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LIST OF SYMBOLS

A	=	Mechanical Damping Coefficient (kg/m^3-s)
A_p	=	Amplitude of the Sound Wave (m)
B	=	Adiabatic Bulk Modulus of Elasticity ($kg/m\text{-}s^2$)
c	=	Velocity of Sound
c_p	=	Specific Heat Capacity at Constant Pressure(J/kg-K)
c_v	=	Specific Heat Capacity at Constant Volume(J/kg-K)
G	=	Shear Modulus in Solids ($kg/m\text{-}s^2$)
I	=	Intensity of Sound (dB)
I_o	=	Standard Reference Intensity (dB)
m	=	M ass Per Unit Length of String (kg/m)
M	=	Molecular Weight of Gas (g/moles)
N	=	Frequency (Hz)
f	=	Frequency (1/sec)
P	=	Pressure of Sound Wave (N/m^2)
P_o	=	Base Acoustic Pressure (N/m^2)
r	=	Radius of Spherical Wave(m)
r_t	=	Radius of Tube(m)
R	=	Universal Gas Constant (J/mole-K)
S	=	Source Intensity Level (kg/s^3 or $Watt/m^2$ or dB)
T	=	Absolute Temperature of Gas (K)
ν	=	Volume of the Gas (m^3)
v'	=	Particle Velocity(m/s)

LIST OF SYMBOLS
(Continued)

Y	=	Young's Modulus of Elasticity ($kg/m\text{-}s^2$)
v_0	=	Volume of the Gas (m^3)
α'	=	Attenuation Coefficient (dB/m)
α	=	Attenuation Coefficient(1/m)
α_p	=	Attenuation Coefficient, 1/cm
γ	=	Ratio of Specific Heat Capacities, c_p/c_v
κ	=	Appropriate Elastic Constant of a Medium ($kg/m\text{-}s^2$)
λ	=	Wavelength of the Sound Wave (m)
ρ	=	Normal Density of the Medium (kg/m^3)
ρ_o	=	Original Density of Gas (kg/m^3)
δ	=	Mass per unit volume of solid (kg/m^3)
θ_i	=	Angle of Incidence of Sound Wave.
θ_r	=	Angle of Reflection of Sound Wave.

CHAPTER 1

INTRODUCTION

1.1 Overview

The problem of land contamination including that of soil, sediments, rock and groundwater, is a significant problem worldwide. Indeed the estimated global cost of remediation is several times the entire world's GDP. Contamination issues are of paramount for various big organizations like defense with multi-million dollar environmental restoration projects currently underway throughout world.

Contamination due to dumping of hazardous waste is major problem in United states where there are about 50000 contaminated sites throughout." The term hazardous waste means waste or a combination of wastes, which because of quantity, concentration or physical, chemical treatment or infectious characteristics may

- Cause or significantly contribute to an increase in mortality or an increase in serious irreversible, or incapacitating reversible illness
- Pose a substantial or potential hazard to human health or the environment when improperly treated stored, transported, or disposed of, or otherwise managed", (U.S. Environmental Protection Agency, State Decision Makers ' Guide for hazardous waste Management, U.S EPA OSW SW 412, Washington D.C 1977)

Lack of awareness of impact of poor disposal techniques and mishandling of hazardous waste leads to harmful effects not only to human beings but also to the environment. Environmental laws were passed to strongly curb improper release of hazardous waste. The laws include resource conservation and recovery act (RCRA) of 1976, the comprehensive environmental response compensation and liability act

(CERCLA) of 1980, The superfund amendments and reauthorization Act (SARA) of 1986.The complete EPA treaty is documented in May 19, 1986 issue of federal register which classified wastes as hazardous or not. "Substances like spent halogenated solvents that are used for degreasing, such as trichloroethylene, methylene chloride, spent nonhalogenated solvents such as xylene, acetone, ethyl benzene, ethyl ether, wastewater treatment sludge, and dewatered air pollution control scrubber sludge from coke ovens and blast furnaces are listed as hazardous materials. Wastes like domestic sewage, irrigation return flows, mine tailings, animal manure, fly ash, wastes from oil and natural gas are listed as non hazardous materials." (U.S Environmental Protection Agency, State Decision Makers Guide for Hazardous Waste Management,U.S EPA OSW SW 412, Washington D.C 1977)

The need for removal of contaminants from various sites leads to development of research in this area. A number of companies have developed and large sums money have been spent on improvisation of technologies for contaminant removal. The research group HSMRC at NJIT developed a new technology called Pneumatic Fracturing. Beginning in 1997 the feasibility of utilizing pneumatic based ultrasonic devices coupled with pneumatic fracturing and vapor extraction was investigated in enhancing the removal of volatile organic compounds from soils. Subsequent research in both the laboratory and the field showed that sonic energy greatly improved the rate of removal of volatile organic compounds from soil. The present research is aimed at reducing the remediation time and doing long-range tests to consolidate previous data.

1.2 Research Objectives and Scope

The present research is focused on the determination of the optimization for the best whistle for the further research in the field at Hillsborough, New Jersey. The above research also focuses on the various drawbacks of previous research studies and also compares these results with the previous research studies. It will conclude with an extended study of attenuation using sonic energy focused at an artificial soil fracture in the siltstone vadose zone located at the Derelco site in Hillsborough, New Jersey.

CHAPTER 2

BACKGROUND OF THE STUDY

2.1 Overview of Current Remediation Technologies

Approximately 85% of the hazardous waste sites in the United States have contaminated ground water. The conventional approach for remediating contaminated ground water has been to extract the contaminated water, treat it above ground, and reinject or discharge the clean water in a process known as "pump-and-treat." The recovered contaminants must be disposed of separately. Pump-and-treat technologies require considerable investment over an extended period of time, and it has been shown that these technologies often do not actually remove the source of the contamination. Current policies and laws stress "permanent" remedies over simple containment methods. Consequently, there is considerable interest in and effort being expended on alternative, innovative treatment technologies for contaminated ground water. (Kaleem, 1999)

2.2 Remediation Technologies

The remediation technologies can be classified in two main categories. The first one is ***ex situ*** which involves excavation to off site facilities for treatment and then returned to its original site. The second is ***in situ*** which involves the treatment of contaminated soil where it is found. Various ***in situ*** technologies which are being used for remediation purposes are the following :

2.2.1 *In Situ* Remediation Technologies

2.2.1.1 Permeable Reactive Barrier: A Permeable Reactive Barrier (PRB) is a passive ***in situ*** treatment zone of reactive material that degrades or immobilizes contaminants as ground water flows through it. PRBs are installed as permanent, semi-permanent, or replaceable units across the flow path of a contaminant plume. Natural gradients transport contaminants through strategically placed treatment media. "The media degrade, sorb, precipitate, or remove chlorinated solvents, metals, radionuclides, and other pollutants. These barriers may contain reactants for degrading volatile organics, chelators for immobilizing metals, nutrients and oxygen to enhance bioremediation, or other agents". (EPA, http://www.gwrtac.org)

2.2.1.2 Ground Water Circulation: Ground-water circulation well systems create a circulation pattern in the aquifer by drawing water into and pumping it through the well, and then reintroducing the water into the aquifer without bringing it above ground. Depending upon the configuration of the system, the technology is also known as in-well vapor stripping, in-well air stripping, ***in situ*** vapor stripping, ***in situ*** air stripping, and vacuum vapor extraction.

2.2.1.3 Chemical Oxidation(*in situ*) : ***In situ*** Chemical Oxidation is based on the delivery of chemical oxidants to contaminated media in order to either destroy the contaminants by converting them to innocuous compounds commonly found in nature. The oxidants applied in this process are typically hydrogen peroxide (H_2O_2), potassium permanganate ($KMnO_4$), ozone, or, to a lesser extent, dissolved oxygen (DO) (EPA, http://www.gwrtac.org)

2.2.1.4 Thermal Enhancement: Both radio frequency (RF) and electrical resistance(alternating current or AC) heating are effective in expelling organic contaminants from soil even in low permeability, clay-rich zones. The electrical properties of the clay zones have been shown to preferentially capture the RF or AC energy, focusing the power in the target zones. "By selectively heating the clays to temperatures at or above 100 C, the release and transport of organics can be enhanced by: (1) an increase in the contaminant vapor pressure and diffusivity; (2) an increase in the effective permeability of the clay with the release of water vapor and contaminant; (3) an increase in the volatility of the contaminant from in situ steam stripping by the water vapor; and, (4) a decrease in the viscosity which improves mobility. The technology is self-limiting; as the clays heat and dry, current will stop flowing. In sandy, more permeable formations, steam can be injected. The advancing pressure front displaces soil, water, and contaminants by vaporization. The organics are transported in the vapor-phase to the condensation front where they condense and can be removed by pumping. The injection of moderately hot water (50 C) in a contaminated zone can increase the solubility of many free-phase organics, which improves their removal by pumping. However, a more important mechanism may be the reduction of viscosity of these free-phase liquids allowing the hot water to displace them. Hot water does not create as harsh an environment as other heating methods and the biomass may be enhanced to remove residuals". (EPA, http://www.gwrtac.org)

2.2.1.5 Electrokinetics: Electrokinetics is a process that separates and extracts heavy metals, radionuclides, and organic contaminants from saturated or unsaturated soils, sludges, and sediments. A low intensity direct current is applied across electrode pairs that have been implanted in the ground on each side of the contaminated soil mass. The electrical current causes electro osmosis and ion migration, which move the aqueous phase contaminants in the subsurface from one electrode to the other. Contaminants in the aqueous phase or contaminants desorbed from the soil surface are transported towards respective electrodes depending on their charge. The contaminants may then be extracted to a recovery system or deposited at the electrode. Surfactants and complexing agents can be used to increase solubility and assist in the movement of the contaminant. Also, reagents may be introduced at the electrodes to enhance contaminant removal rate.

2.2.1.6 Solvent Flushing: ***In situ*** solvent flushing involves injecting a solvent mixture (e.g., water plus a miscible organic solvent such as alcohol) into the vadose zone, the saturated zone, or both to extract organic contaminants.

2.2.1.7 Hydro Fracturing: Hydraulic fracturing creates distinct sand-filled fractures in low permeability and over-consolidated clays or sediments. High-pressure water is first injected into the bottom of a borehole to cut a disk shaped notch that serves as the starting point for the fracture. Slurry of water, sand, and a thick gel is pumped at high pressure into the borehole to propagate the fracture. The residual gel biodegrades and the resultant fracture is a highly permeable sand-filled lens that may be as large as 60 feet in diameter. The fractures serve as avenues for bioremediation, steam or hot air injection or contaminant recovery and can also improve pumping efficiency and the delivery for other ***in situ*** processes. Precise measurement of ground elevation before and after fracturing allows for a determination of the fracture thickness and lateral location. Other granular materials such as graphite can be used instead of sand to create fractures with different properties. (EPA, http://www.gwrtac.org)

2.2.1.8 Pneumatic Fracturing: The pneumatic fracturing process involves injection of highly pressurized air into consolidated sediments that are contaminated to extend existing fractures and create a secondary network of fissures and channels. This enhanced fracture network increases the permeability of the soil to liquids and vapors and accelerates the removal of contaminants, particularly by vapor extraction, biodegradation, and thermal treatment.

2.2.1.9 Sonic Remediation: This method of soil remediation is currently being developed. Potential applications of ultrasound are to disperse tightly packed clays in wells and soils, to enhance the rate of chemical reactions, and to help eliminate the undesired microbes that can possibly clog pore spaces in soils (Fernandez, 1997).

2.2.2 *Ex Situ* Remediation Techniques

These techniques involve excavating and transporting the contaminated soils to a location where removal of the volatile organic compounds can occur. Then the remediated soil can be returned to the original site or placed elsewhere. The result of the procedures is a higher cost of operation than current ***in situ*** techniques (Bootwala, 1999).

2.2.2.1 Secure Landfill : In this technique it is intended that a secure landfill will hold the organic hazardous wastes in as concentrated a form as possible for an indefinite period of time (Kaleem, 1999).

2.2.2.2 Hazardous Waste Treatment Facility: At these facilities organic and inorganic wastes are either incinerated or treated to yield a liquid effluent that is considered non-toxic and a concentrated sludge, which is then sent to a secure landfill (Kaleem, 1999).

2.2.2.3 Co-disposal: Involves the co-disposal of hazardous waste with municipal refuse. The idea is based on the concept that large amounts of refuse can absorb relatively small amounts of hazardous inorganic liquid wastes and some organic liquid wastes so that the result is decontamination by the refuse and surrounding soil (Henry and Heinke, 1989).

2.2.2.4 Thermal Treatment: This method involves treatment of contaminated soil by subjecting it to high temperatures (1200°F or greater).

2.3 Overview of Acoustics

2.3.1 Definition of Sound Wave. (Wilson, 1989)

Sound is a mechanical disturbance from a state of equilibrium that propagates through an elastic material medium. A purely subjective definition of sound is also possible, as that which is perceived by the ear, but such a definition is not particularly illuminating and is unduly restrictive, for it is useful to speak of sounds that cannot be heard by the human ear, such as those that are produced by dog whistles or by sonar equipment.

"The study of sound should begin with the properties of sound waves. There are two basic types of wave, transverse and longitudinal, differentiated by the way in which the wave is propagated. In a transverse waves, such as the wave generated in a stretched rope when one end is wiggled back and forth, the motion that constitutes the wave is perpendicular, or transverse, to the direction (along the rope) in which the wave is moving. An important family of transverse waves is generated by electromagnetic sources such as light or radio, in which the electric and magnetic fields constituting the wave oscillate perpendicular to the direction of propagation". (Albers, 1970)

Sound propagates through air or other mediums as a longitudinal wave, in which the mechanical vibration constituting the wave occurs along the direction of propagation of the wave. A longitudinal wave can be created in a coiled spring by squeezing several of the turns together to form compression and then releasing them, allowing the compression to travel the length of the spring. Air can be viewed as being composed of layers analogous to such coils, with a sound wave propagating as layers of air "push" and "pull" at one another much like the compression moving down the spring. (Wood, 1941)

A sound wave thus consists of alternating compressions and rarefactions, or regions of high pressure and low pressure, moving at a certain speed. Put another way, it consists of a periodic (that is, oscillating or vibrating) variation of pressure occurring around the equilibrium pressure prevailing at a particular time and place. Equilibrium pressure and the sinusoidal variations caused by passage of a pure sound wave (that is, a wave of a single frequency).

"Sound is propagated through a medium as a compression wave, meaning that the medium will be both compressed and expanded alternately as the wave moves through it. The particles of the air will move back and forth parallel to the propagation of the sound wave.

When the medium is compressed its pressure will increase above the steady state pressure, and when it is expanded its pressure will decrease to a value below that of a steady state pressure. Sound pressure is therefore determined by the variation in pressure that takes place as the sound wave passes a point in the medium. The sound pressure factor of a sound wave in a medium is very important because most of the sound detecting devices including the human ear respond to the sound pressure." (Wood, 1941)

Sound, to humans, is a compression wave that produces a sensation in the human ear. The human ear typically responds to a frequency range of 20 - 20,000 Hz (the audible range). The frequency range below the audible range is referred to as the infrasonic range of frequencies; the audible range is also known as the sonic range of frequencies, and the range of frequencies above the audible range is called the ultrasonic range (Bootwala, 1999).

Sound is, simply put, a mechanical wave. A mechanical wave is a disturbance from some equilibrium position in a homogenous continuous material (Fernandez, 1997). The disturbances create a mechanical wave, which travels through the medium slowly diminishing in strength as the wave moves away from its source. Mechanical waves can be put into either the transverse wave category or the longitudinal wave category. A transverse wave displaces the medium perpendicular to the direction of propagation to the wave's travel (Sears, 1986). Contrasting to this is a longitudinal wave, which creates medium displacement in the same direction as wave propagation.

Sound waves in gases and liquids are longitudinal waves whereas those in solids can be either transverse or longitudinal waves. Mechanical waves only transport energy but no matter through the medium (Fernandez, 1997).

2.3.2 The Decibel scale

Sound intensity is usually given on a logarithmic scale, because normal sound has tremendous variations of intensities and also to allow for the dynamic characteristics of the human ear. The logarithmic scale used is called the decibel scale (dB). The decibel scale allows for intensity to be expressed by calculating its value with reference to some standard intensity, I_o, usually accepted to be 10^{-12} watts/m^2, which is just below the human hearing threshold (Albers, 1970). The sound intensity in decibels is shown as (Bootwala, 1999):

$$I\,(\text{dB}) = 10 \log_{10} (I / I_o) \qquad (2.1)$$

So the decibel scale shows a sound intensity ten times greater than another sound intensity as being 10dB larger. Bootwala (1999) offers some examples of sounds and the sound intensities, in decibels, that they generate; the rustling of leaves, 10 dB; normal human conversation, 40 – 70 dB; a pneumatic drill, 90dB; and a jet engine 100 – 120 dB. Any value of sound intensity above 130 dB is not understood by the human ear as a sound, but is experienced instead as pain.

2.3.3 Velocity of Sound

Mechanical waves travel through a continuous homogenous material at a constant speed, which is known as wave speed. The wave's velocity through the medium is dependent on the fundamental physical properties of elasticity and density.

The velocity c of the sound wave in a medium is given by (Wood, 1941):

$$c = \sqrt{(\kappa/\rho)} \qquad (2.2)$$

where κ is the appropriate elastic constant and ρ is the normal density of the medium.

2.3.4 Velocity of Sound in Gases

For longitudinal waves such as sound, wave velocity is in general given as the square root of the ratio of the elastic modulus of the medium (that is, the ability of the medium to be compressed by an external force) to its density. The velocity of sound in gases can be determined by substituting the constant *B*, the adiabatic Bulk Modulus of Elasticity, in place of κ (Wood, 1941):

$$c = \sqrt{(B/\rho)} \qquad (2.3)$$

It was found experimentally that sound travels in a gas or air adiabatically. (Sears, 1986). The derivation of the velocity of sound for adiabatic propagation of sound in air given above yields (Sears, 1986):

$$c = \sqrt{(\gamma P/\rho)} \quad = \sqrt{(\gamma RT/M)} \qquad (2.4)$$

Where P is the pressure of the sound wave at density ρ, R is the universal gas constant, T is the absolute temperature (°K), M is the molecular weight of the gas, and γ is the ratio of specific heat capacities of an ideal gas at constant pressure to that at constant volume.The bulk modulus of elasticity, *B*, is given by (Wood, 1941):

$$B = v_0\,(dp/dv) = \rho_0\,(dp/d\rho) \qquad (2.5)$$

where v_0 and ρ_0 are the original volume and density of the gas respectively.

Since the relationship between pressure and density is constant for a given temperature, the change in pressure has no influence on the velocity. However, the density of a gas changes with temperature at constant pressure, and hence another relationship between velocity of sound and temperature (derived from Equation 2.4) is defined as (Wood, 1941):

$$c \propto \sqrt{T} \qquad (2.6)$$

Relationship 2.5 shows that velocity c varies directly with the square root of the absolute Temperature, T.

2.3.5 Velocity of Sound in Liquids and Homogeneous Solids

As mentioned above, when sound waves travel through isotropic and homogeneous solids, two kinds of waves, longitudinal and transverse, can propagate through the solids. When a longitudinal wave is propagating through an isotropic solid, the speed of sound is related to the amount of compression that a material can endure. The amount of compression and stretching is small and the speed of sound in that solid is related to Young's Modulus of Elasticity in the solid by the following equation (Fernandez, 1997):

$$c = \sqrt{(Y/\rho)} \qquad (2.7)$$

where Y is Young's Modulus of Elasticity and ρ is the density of the isotropic solid.

A transverse wave is when a pulsing shear force is applied to an isotropic homogeneous solid. This process creates a wave front that propagates perpendicular to the medium through which it is traveling. The velocity of a transverse wave in an isotropic solid is related to tension, S, of the solid and the mass per unit volume, δ, as follows (Fernandez, 1997):

$$c = \sqrt{(S/\delta)} \qquad (2.8)$$

Equation 2.8 shows that the more tension a solid medium possesses, the faster the transverse component of sound will travel and the more mass per unit volume, the slower sound will travel. When dealing with liquids, no transverse waves can exist because any shear force applied to liquid will dissipate immediately due to the low viscosity of liquids compared to solids (Fernandez, 1997).

2.3.6 Acoustic Wave Energy

A wave's energy is measured by its intensity, which is the average power transported per unit area through the surface which is perpendicular to the direction of travel (Sears, 1986). The derivation is performed by Sears (1986) to produce an equation representing average intensity of a sound wave moving through a gaseous medium:

$$I = \tfrac{1}{2}\ c(2\pi/\lambda)^2\ BA_p^2 \qquad (2.9)$$

Where I is intensity, wavelength is represented by λ, and A_p is the amplitude of the sound wave. The most important variable in this equation, in terms of intensity, is the amplitude A_p, because the intensity will increase by the square of the amplitude.

When dealing with a medium other than gas, sound intensity is given by (Albers, 1970):

$$I = (P^2/\ \rho c) \qquad (2.10)$$

As in Equation 2.9, one variable for sound intensity dominates the results. In Equation 2.10 the intensity of the sound wave is directly proportional to the square of the sound pressure, P.

2.3.7 Sound Attenuation

"A plane wave of a single frequency in theory will propagate forever with no change or loss. This is not the case with a circular or spherical wave, however. One of the most important properties of this type of wave is a decrease in intensity as the wave propagates. The mathematical explanation of this principle, which derives as much from geometry as from physics, is known as the inverse square law.

As a circular wave front (such as that created by dropping a stone onto a water surface) expands, its energy is distributed over an increasingly larger circumference. The intensity, or energy per unit of length along the circumference of the circle, will therefore decrease in an inverse relationship with the growing radius of the circle, or distance from the source of the wave. In the same way, as a spherical wave front expands, its energy is distributed over a larger and larger surface area. Because the surface area of a sphere is proportional to the square of its radius, the intensity of the wave is inversely proportional to the square of the radius. This geometric relation between the growing radius of a wave and its decreasing intensity is what gives rise to the inverse square law.

The decrease in intensity of a spherical wave as it propagates outward can also be expressed in decibels. Each factor of two in distance from the source leads to a decrease in intensity by a factor of four. For example, a factor of four decrease in a wave's intensity is equivalent to a decrease of six decibels, so that a spherical wave attenuates at a rate of six decibels for each factor of two increase in distance from the source. If a wave is propagating as a hemispherical wave above an absorbing surface, the intensity will be further reduced by a factor of two near the surface because of the lack of contributions of Huygens' wavelets from the missing hemisphere. Thus, the intensity of a wave propagating along a level, perfectly absorbent floor falls off at the rate of 12 decibels for each factor of two in distance from the source. This additional attenuation leads to the necessity of sloping the seats of an auditorium in order to retain a good sound level in the rear". (Albers, 1970)

When wave energy propagates through a medium, some of the energy is lost due to deflection of the wave energy by scattering, diffraction, refraction and reflection (terms that will be discussed later in this chapter). Energy possessed by a wave can also be absorbed or lost when the sound energy is converted into heat by internal friction in the medium.

The frequency and amplitude play a dramatic role in the attenuation of sound intensity. For frequency the amount of attenuation is controlled by the viscosity and heat conduction of the medium. With waves of very high frequencies, the effects of viscosity and heat conduction are dramatic, but with waves of very low frequencies, the attenuation is negligible. For waves with frequencies that lie somewhere between the two extremes of high and low, the effects of viscosity and heat conduction will only be partially expressed. When dealing with the role of amplitude, the loss of wave energy is due to the transfer of heat from a region of higher pressure to an area of lower pressure. This transfer is driven by the nature of the medium to achieve an equalized pressure. The medium is therefore trying to retard the wave by equalizing pressures. This is only a real factor in sound intensity attenuation when dealing with a wave that has large amplitude.

In air the amount of water vapor present can greatly affect the attenuation of sound. An increase in water vapor concentration in the air will markedly increase the amount of sound attenuation (Barber, 1992). The observed absorption of sound in moist air is 10 – 100 times that in dry air (Bootwala, 1999). Overall, it can be stated that increasing the levels of impurities in air will have an increased affect on sound absorption.

One other mechanism by which sound wave energy is reduced in air is thermal relaxation. Thermal relaxation is the conversion of wave energy into internal kinetic energy of the air, thereby decreasing wave energy.

In solids, attenuation in decibels is shown as the product of the attenuation coefficient, α, expressed in decibels per yard or decibels per meter, and the distance, r, in yards or meters respectively. So the intensity at any range due to an initial intensity, I, is expressed as (Officer, 1958):

$$I = S\,(1/r^2)e^{(-\alpha r)} \qquad (2.11)$$

where S is the source level. Transferring it into decibels (Officer, 1958):

$$I\,(\text{dB}) + 20 \log r = S\,(\text{dB}) - \alpha' r \qquad (2.12)$$

Plotting (I (dB) + 20 log r) versus r will result in a straight line. The slope of this resulting line will be equal to the loss in decibels per unit distance, $-\alpha$ (Officer, 1958).

A more simplistic and practical equation for finding the attenuation coefficient can be given by (Hunter, 1999):

$$\alpha = (a / 2\rho c) \qquad (2.13)$$

In Equation 2.13 the attenuation coefficient is solved in terms of a, the mechanical damping coefficient. It is also observed that low frequency sound travel further through air than high frequency sound. With humidity it is observed that at high humidity the attenuation is less and it increases with frequency for constant humidity. (Barber, 1992)

2.3.8 Sound Absorption

In addition to the geometric decrease in intensity caused by the inverse square law, a small part of a sound wave is lost to the air or other medium through various physical processes. One important process is the direct conduction of the vibration into the medium as heat, caused by the conversion of the coherent molecular motion of the sound wave into incoherent molecular motion in the air or other absorptive material. Another cause is the viscosity of a fluid medium (i.e., a gas or liquid). These two physical causes combine to produce the classical attenuation of a sound wave. Although attenuation is rather small for audible frequencies, it can become extremely large for high-frequency ultrasonic waves. Attenuation of sound in air also varies with temperature and humidity.

Because less sound is absorbed in solids and liquids than in gases, sounds can propagate over much greater distances in these mediums. For instance, the great range over which certain sea mammals can communicate is made possible partially by the low attenuation of sound in water. In addition, because absorption increases with frequency, it becomes very difficult for ultrasonic waves to penetrate a dense medium. This is a persistent limitation on the development of high-frequency ultrasonic applications.

Most sound-absorbing materials are nonlinear, in that they do not absorb the same fraction of acoustic waves of all frequencies. In architectural acoustics, an enormous effort is expended to use construction materials that absorb undesirable frequencies but reflect desired frequencies. Absorption of undesirable sound, such as that from machines in factories, is critical to the health of workers, and noise control in architectural and industrial acoustics has expanded to become an important field of environmental engineering. Richardson (1935) has shown that intensity varies exponentially with distance. The equation is

$$I = I_o e^{(-\alpha r)} \qquad (2.14)$$

where α is the attenuation coefficient and r is the distance.

2.3.9 Diffraction

"A direct result of Huygens' wavelets is the property of diffraction, the capacity of sound waves to bend around corners and to spread out after passing through a small hole or slit. If a barrier is placed in the path of half of a plane wave, a the part of the wave passing just by the barrier will propagate in a series of Huygens' wavelets, causing the wave to spread into the shadow region behind the barrier. In light waves, wavelengths are very small compared with the size of everyday objects, so that very little diffraction occurs and a relatively clear shadow can be formed. The wavelengths of sound waves, on the other hand, are more nearly equal to the size of everyday objects, so that they readily diffract.

Diffraction of sound is helpful in the case of audio systems, in which sound emanating from loudspeakers spreads out and reflects off of walls to fill a room. It is also the reason why 'sound beams' cannot generally be produced like light beams. On the other hand, the ability of a sound wave to diffract decreases as frequency rises and wavelength shrinks. This means that the lower frequencies of a voice bend around a corner more readily than the higher frequencies, giving the diffracted voice a "muffled" sound. Also, because the wavelengths of ultrasonic waves become extremely small at high frequencies, it is possible to create a beam of ultrasound. Ultrasonic beams have become very useful in modern medicine.

The scattering of a sound wave is a reflection of some part of the wave off of an obstacle around which the rest of the wave propagates and diffracts. The way in which the scattering occurs depends upon the relative size of the obstacle and the wavelength of the scattering wave. If the wavelength is large in relation to the obstacle, then the wave will pass by the obstacle virtually unaffected. In this case, the only part of the wave to be scattered will be the tiny part that strikes the obstacle; the rest of the wave, owing to its large wavelength, will diffract around the obstacle in a series of Huygens' wavelets and remain unaffected. If the wavelength is small in relation to the obstacle, the wave will not diffract strongly, and a shadow will be formed similar to the optical shadow produced by a small light source. In extreme cases, arising primarily with high-frequency ultrasound, the formalism of ray optics often used in lenses and mirrors can be conveniently employed. " (Wood, 1941)

If the size of the obstacle is the same order of magnitude as the wavelength, diffraction may occur, and this may result in interference among the diffracted waves. This would create regions of greater and lesser sound intensity, called acoustic shadows, after the wave has propagated past the obstacle. Control of such acoustic shadows becomes important in the acoustics of auditoriums (Wood, 1941).

2.3.10 Refraction

Diffraction involves the bending or spreading out of a sound wave in a single medium, in which the speed of sound is constant. Another important case in which sound waves bend or spread out is called refraction. This phenomenon involves the bending of a sound wave owing to changes in the wave's speed. Refraction is the reason why ocean waves approach a shore parallel to the beach and why glass lenses can be used to focus light waves. An important refraction of sound is caused by the natural temperature gradient of the atmosphere.

Refraction occurs when a wave front travels from one medium, where the velocity of the wave propagation, c_1, into another medium where that new wave velocity is now c_2. The result is a change in direction of the rays unless they are perpendicular to the surface of the medium. The angle of transmission for the sound wave is related to the sound wave's angle of incidence through Snell's Law (Fernandez, 1999):

$$\sin \theta i / c_1 = \sin \theta r / c_2 \qquad (2.15)$$

However, if the angle of incidence is greater than the critical angle, the sound wave is completely reflected back to the medium from which it came and no transmission occurs (Bootwala, 1999).

2.3.11 Reflection

"A property of waves and sound quite familiar in the phenomenon of echoes is reflection. This plays a critical role in room and auditorium acoustics, in large part determining the adequacy of a concert hall for musical performance or other functions. In the case of light waves passing from air through a glass plate, close inspection shows that some of the light is reflected at each of the air-glass interfaces while the rest passes through the glass. This same phenomenon occurs whenever a sound wave passes from one medium into another--that is, whenever the speed of sound changes or the way in which the sound propagates is substantially modified". (Officer, 1958).

Sound waves are reflected back into the medium of origin, when the wave encounters a discontinuity or an interphase between the medium where it is propagating and the other medium with which it has an encounter (Fernandez, 1997). Sound waves will reflect at the angle of incidence (Fernandez, 1997):

$$\theta i = \theta r \tag{2.16}$$

where θi represents the angle of incidence and θr represents the angle of reflection.

2.3.12 Impedance

One of the important physical characteristics relating to the propagation of sound is the acoustic impedance of the medium in which the sound wave travels. Acoustic impedance is given by the ratio of the wave's acoustic pressure to its volume velocity. Like its analogue, electrical impedance (or electrical resistance), acoustic impedance is a measure of the ease with which a sound wave propagates through a particular medium. Also like electrical impedance, acoustic impedance involves several different effects applying to different situations. For example, specific acoustic impedance, the ratio of acoustic pressure to particle speed, is an inherent property of the medium and of the nature of the wave. Acoustic impedance, the ratio of pressure to volume velocity, is equal to the specific acoustic impedance per unit area. Specific acoustic impedance is useful in discussing waves in confined mediums, such as tubes and horns. For the simplest case of a plane wave, specific acoustic impedance is the product of the equilibrium density of the medium and the wave speed.

The unit of specific acoustic impedance is the pascal second per meter, often called the rayl, after Lord Rayleigh. The unit of acoustic impedance is the pascal second per cubic meter, called an acoustic ohm, by analogy to electrical impedance.

2.3.13 Divergence

Under normal conditions, it is commonly experienced that a sound's intensity quickly dissipates as one travels away from the sound source. As explained earlier, the intensity of a sound is expressed as the energy of the wave per unit area. Taking this into consideration and the Principle of Conservation of Energy it is clear why divergence occurs. When a sound is generated from a source its waves move away as an expanding sphere. As the wave front continues to expand, the energy remains constant while the area of the spherical wave front continually changes. Thus, total energy can be equated by (Richardson, 1935)

$$I_1 \, 4 \, \pi \, r_1^2 = I_2 \, 4 \, \pi \, r_2^2 \tag{2.17}$$

or (Officer, 1958):

$$I = S \, (1/r^2) \tag{2.18}$$

or using Equation 2.1:

$$I \, (\text{dB}) = S \, (\text{dB}) - 20 \log_{10} r \tag{2.19}$$

All of the above equations demonstrate that there is a decrease in the sound intensity with distance due to divergence. It is important to note that on the decibel scale, for each time the distance, r, is doubled from the source the intensity decrease due to divergence by 6 decibels.

There are two practical problems with calculating divergence. First, these Equations (2.17 –2.19) do not consider the attenuation of sound due to loss of energy dispersal in friction and heat. Secondly, the divergence discussion above assumes that a sound source is a point. The production of a sound source from a single pinpoint is not possible, so Equations (2.17 –2.19) will not produce accurate solutions.

2.4 Acoustic Properties of Soil

The nature of a soil determines the acoustic properties of that soil. The acoustic properties such as attenuation of sound, amplitude of a sound wave, and the speed of a sound in a soil depend upon the soil's consolidation, type of minerals present, moisture content, and porosity (Blangy et al., 1993). In tightly packed clays, sound travels more readily than in unconsolidated soils, which tend to inhibit sound travel. So, it has been concluded that tightly packed clays can be considered homogeneous media for sound to travel through (Han et al., 1986), while unconsolidated sediments, such as sand, should be considered heterogeneous (White, 1965). Table 2.1 has the attenuation coefficients of sound waves for various rock types.

Table 2.1 Measured Attenuation Coefficients of Several Rock Types (from White, 1965)

ROCK TYPE	FREQUENCY (cps)	ATTENUATION COEFFICIENT (α_p)	METHOD
Granite: Kamyk	1×10^6 $(0.2\text{-}2) \times 10^6$	$0.044\ cm^{-1}$ $3.9 \times 10^{-8} f$ sec/cm	Multiple reflection of sine-wave train Short Pulse, direct path
Limestone: Solnhofen	$(3\text{-}15) \times 10^6$	$5.2 \times 10^{-8} f$ sec/cm	Multiple reflection of sine-wave train
Sandstone: Amherst	1×10^6	$0.035\ cm^{-1}$	Multiple reflection of sine-wave train
Chalk: Chiselhurst	600	$6 \times 10^{-6}\ cm^{-1}$	Bulk medium, sine-wave train
Shale: Sylvan	$(3\text{-}12) \times 10^3$ $(6\text{-}20) \times 10^3$	$45 \times 10^{-8} f$ sec/cm $4 \times 10^{-6} f$ sec/cm	Long. Reconance Bulk medium, Fourier analysis of pulses

2.5 Sonic Generators

Currently, five major types of sound generators are available. The different types vary in accordance with how they generate sound and the materials of which they are constructed (Fernandez, 1997). The five categories of sound generators are as follows:

- ❖ Electrostatic Generators
- ❖ Electrodynamic Generators
- ❖ Magnetostrictive Generators
- ❖ Piezoelectric Generators
- ❖ Pneumatic Generators

Electrostatic generators are based on the governing principle that the spacing between the plates of the condenser can change generating sonic energy. The plates are made up of flexible metallic materials, which attract and repel the other plate in the presence of an alternating current. The resulting motion of the plates generates sound vibrations in the air around the plates (Fernandez, 1997). These generators application involve distance measurement and sound editing.

The driving principle behind all electrodynamic generators is that an electric current creates a magnetic field, causing vibrations in a magnetic plate, when it is passed through a coil. The vibration of the magnetic plate results in resonance and sound being generated. Electrodynamics generators are one most common sound generators in the market.

Magnetostrictive generators are based on the idea that when a voltage is applied to a metallic material, the material will expand and when the voltage is eliminated; the metallic material will go back to its initial shape (Fernandez, 1997). When an alternating positive and negative voltage is applied to the material a series of vibrations are produced and thus sound. These sound generators are noted for their durability and are most often used for cleaning mechanical parts with the aid of cleaning fluids.

The principle that governs the piezoelectric generators is build upon the fact that a crystal with piezoelectric properties will develop a charge when brought into contact with a voltage (Bootwala, 2000). The charged crystal will be attracted to the other oppositely charged crystals. A reversal of the current causes the charge and attractive nature of the crystal to reverse. When alternation between voltages occurs, the crystal will vibrate. If the crystal vibrates at its resonance frequency, the result is the generation of a sound field (Fernandez, 1997). Piezoelectric generators are the most commonly used industrial sound generators in the market today.

Pneumatic generators need to be broken down into two separate categories, static generators and dynamic generators, both of which use air to produce sound.
The generation of sound in a static generator is based upon a jet of air emerging from a converging nozzle, close to the speed of sound, which then generates waves at the tip of the nozzle (Fernandez, 1997). When a resonant cavity is placed in the path of the air jet, a sound wave is produced. The predominant static pneumatic generators used are whistles. It is important to note that whistles have a major advantage over dynamic pneumatic generators in that whistles have no moving parts.

Dynamic generators operate on the principle that when a rotating device is allowed to interrupt a jet of air at a constant rate, a sound wave is generated. An example of a dynamic pneumatic generator is a siren.

This research project used a whistle as a sonic generator. The selection was based on previous laboratory work done by Fernandez (1997) and Bootwala (2000) and the fact, presented by Kaleem (1999), that a whistle is more mechanically reliable than a siren.

2.6 Previous Studies in Project

The enhancement of pneumatic fracturing and vapor extraction performance with the use of sonic energy to decontaminate soil, ***in situ*** is a relatively new and developing technology. This method, a basis for this study, has been repeatedly and conclusively shown to enhance remediation in previous laboratory and field studies (Fernandez, 1997; Kaleem, 1999; Lin, 1999; Bootwala, 1999). All of these investigations and previously conducted studies concluded that focusing sonic energy into a soil fracture coupled with vapor extraction can generate an enhancement in the removal rates of fluids that are trapped in tightly packed soils.

2.6.1 Hugo Fernandez's Study (Fernandez, 1997)

Through laboratory tests, the drying of solids associated with an sonic field showed that several effects occurred when a sonic intensity of nearly 125dB (siren) and 160 dB (whistle) was sent through a fracture at sonic frequencies of 17 kHz and 11 kHz respectively.

The first effect is when a sound field is focused into a fracture a decrease in the gas-liquid interface film occurs. This occurs through the build-up of regional turbulence because of the presence of a sonic field. The lowering of the interface film allows for an increase in both mass and heat transfer and thus more liquid can be evaporated.

The second effect is the lowering of the net total pressure inside the fracture where sonic energy is applied. The sonic energy causes compression and dilation of the air within the fracture. The creation of compressions and dilations lowers the net total pressure inside the fracture because dilation regions control compression regions. The resulting lower net total pressure allows more of the liquid in the fractures to vaporize and be transported out of the soil by the air stream. A pressure gradient also forms from the lowering of the net total pressure, which acts as a driving force for vapor to move in the direction of the fractures.

The third noted effect is that liquids cavitate when a sonic field of 160 dB is focused within a fracture. It is hypothesized that the effect of cavitation may increase the removal rate of contaminants is soils. (Zarnetske, 2000)

The laboratory studies tested the possibility of enhancing the removal of volatile organic compounds in soil through the coupling of air flow rates with sonic energy. It was conclusive that sonic energy does enhance the removal of VOCs in the soil. The enhancement results were dramatic with siren-generated sonic energy causing a 192% increase in ethanol removal, and a staggering 931% removal increase with the whistle producing the sonic energy. In terms of contaminant removal rates, the siren decreased the time by 41% and the whistle by 74%.

2.6.2 Hassan Kaleem's Study (Kaleem, 1999)

As a continuation of Fernandez's study (1997), Kaleem (1999) performed similar tests in the field on a New Jersey site contaminated with trichloroethylene and dichloroethylene. This time the sonic generator used was a whistle exclusively, which tested at a maximum intensity of 160 dB at the source. The study analyzed contaminant removal concentrations and removal rates over periods of using sonic energy and not using sonic energy. The results were that sonic energy produced a 38% increase in the removal rate and a 21% increase in the concentration of trichloroethylene removed. This study recommended that investigations be made into the decay of sonic intensity in the fractures and to find the corresponding attenuation coefficients in the soil, which Bootwala's work (1999) and this research project are hoping to achieve.

2.6.3 Chin-Yu Lin's Work (Lin, 1999)

This was a laboratory study investigating the effects of applied sonic energy frequency, coupled with the soil fracturing and vapor extraction, on the contaminant (VOCs) removal rates from low-permeability soils. In order to vary frequency of the sonic energy a siren was used to conduct the experiment. This study selected a siren frequency range of 2,957 - 17,677 Hz and a siren intensity of less than 125 dB.

It was concluded that the effect of frequency is not statistically significant with only a slight increase in removal rate with rise in frequency. However, it demonstrated that sound intensity is more important for the enhancement of contaminant removal concentrations and removal rates which was demonstrated by Fernandez in comparing the siren (125 dB, 17 kHz with the whistle (160 dB, 11 kHz)

2.6.4 Minhaz Bootwala's Work (Bootwala, 2000)

This study investigated the attenuation of sound used in coupling sonic energy with pneumatic fracturing and vapor extraction at a field site in New Jersey. Preliminary attenuation studies were performed in the laboratory of Lucent Technologies, Murray Hill, NJ with a microphone made there. Five whistles were tested for sound intensity capabilities and the best performing whistle (sound intensity range of 150-160 dB) was selected to conduct the field study. The attenuation of sound in air was measured in a controlled soundproof laboratory in Murray Hill, NJ. Whistle No. 4 and Whistle No.5 proved to be the best. The field study was conducted at the same site where Kaleem (1999) had shown a considerable increase in the removal rates and removal concentrations of trichloroethylene and dichloroethylene.

Experimental runs were performed where sonic energy of a known intensity was applied at an inlet of an artificial fracture in the soil and its intensity was measured at the outlet of the fractures. These data were expected to indicate the attenuation of the sound in rock and soil, but no sound above a base level ever reached the outlets of the fracture. The conclusion was that sonic energy is being absorbed very quickly in the ground. The rapid attenuation was explained by the random nature of the fractures in the site's soil and rock. (Bootwala, 2000)

2.6.5 Jay Peter Zarnetske's Work (Jan 2000)

This laboratory research was based on earlier fieldwork, which showed that sonic energy attenuates very quickly within soil fractures (Bootwala, 2000). The objective of this study was to test, in the laboratory, the attenuation of sound energy as it moves between two slabs of porous geologic rock with the slab spacing, distance and detection direction as key variables. Zarnetske studied the factors that may control attenuation in a laboratory environment. (Zarnetske, 2000)

The major goals of this research were to determine whether Bootwala's (1999) conclusions were valid, and where his research methodology may have provided misleading results.

Zarnetske kept the slab spacing at 5mm and measured sound intensity at every 20 cm from 20 to 210 cm. In other tests he kept the spacing at the source constant at 18mm and varied the spacing at the detection microphone from 18, 15, 10, 5, 3, 2, 1, 0 mm to test the variation in sound intensity. Readings were taken at the left side, right side, and center of the slabs and the average values were calculated.

With constant spacing of 5mm, the sound intensity decreased from 141.6 dB to 116.7dB as the distance increased from 20 to 210cm. In the second test, the sound intensity detected varied erratically from about 135 to 118dB with the only significant change occurring when the slab thickness was decreased from 1mm to 0 mm. Zarnetske repeated this latter test, but with the opening at the source at 10mm and the spacing at the detection point at 2, 3, 4 and 10mm.The results varied but generally the lower spacing at the detection point resulted in a lower sound intensity. In another test, he studied the effect of the sound proofing material used in his apparatus. Soundproofing has apparatus with foam was superior to wooden blocks.

Zarnetske stated, " the findings of this study demonstrate that ultrasonic sound attenuates less within an artificial fracture than it would in an unrestricted air space. It was also determined that sound rapidly disintegrates after escaping the confines of the artificial fracture. This explained why Bootwala (2000) was unable to detect sound at the exit of the field site fractures, because his microphone placement was greater than 2 cm from the opening of the fracture cavity" (Zarnetske, 2000). This study also produced preliminary results indicating that fracture geometry does affect how sound energy is transferred through a fracture and that certain fracture geometries may increase or decrease the rate that a sound attenuates. (Zarnetske, 2000).

The study recommended to repeat Bootwala's (2000) field research study but develop a procedure and a microphone, which will allow for readings to be taken immediately within the exit cavity of the fracture (Zarnetske, 2000). Since preliminary results obtained in the study indicate fracture geometry may affect how sound energy is transferred, a study focusing on the fracture geometry variability and its affect on sound attenuation should be conducted. It was also recommended to repeat this study's procedures with different frequencies other than 9000Hz and determine if frequency changes the results found in this research project (Zarnetske, 2000) and to test sound attenuation in an artificial fracture that has irregularities in its path from sound source opening to sound exit opening (e.g. changes in fracture direction). A set of experiments could involve a similar setup to this study, but involve drilling offset holes somewhere in the center of the slabs and forming fractures in different directions (Zarnetske, 2000). The whistle would then be placed in these holes giving multiple distances to the end of the slab where the microphone could be located. Zarnetske also recommended to repeat this study with water-saturated slabs in order to simulate the high humidity that might be encountered in field applications. (Zarnetske, 2000)

2.6.6 Antoine Godde's Study, Summer 2000

The objective of his study was to determine the key factors in the propagation of sound within an artificial fracture of controlled width between two porous geologic rock slabs. The influence of the airflow rate on sound intensity was also studied. Godde followed Zaernetske's recommendation. He first varied the airflow rate to the whistle and measured the sound frequency. He studied all five whistles. For Whistle No.3 and No.5, the frequency increased linearly with airflow rate. For Whistle No.2 and No.4, the frequency declined with airflow rate at the lower flow rates, and then increased. For Whistle No.1, the frequency increased slightly , then rapidly to a maximum and then dropped as the flow rate was higher. Whistle No.5 proved to be the best.

Godde repeated Zarnetske's test of keeping the source spacing constant at 10mm and varying the fracture opening at the detection point from 20, 18.75, 14.75, 14.25, 11.2, 9, 6.75, 5.5 and 4 mm. He used the Whistle No.5 only and varied the airflow rate from 6.0, 6.5, 7.0 and 7.5 SCFM. He showed that the variable airflow rate did not gave a linear relationship but that the sound intensity decreased linearly with fracture width with a correlation coefficient R^2 =0.9268. In the next test he reduced the slab spacing at the source from 10 to 5 mm and repeated the test. The lower slab spacing of 5 mm resulted in greater sound intensities. The geometry of the fracture is important and again a linear decrease in sound intensity was observed with decrease in the opening at the detection point. The R^2 value was 0 .9285. He concluded a narrower fracture at the source is better. In another test, he kept the source opening at 5 mm and varied the detection spacing at the end of the slabs from 4, 6.75, 11.2 and 14.75 m. He drilled 3 mm holes in the center line of the slabs and spaced the holes every 10cm from a distance of 30 cm from the whistle to 200cm. He showed that sound intensity declines linearly with distance with a correlation coefficient, $R^2 = 0.954$, when all four airflow rates were studied. Godde showed that the attenuation coefficient varied from 9.4 dB/m at a spacing of 14.75mm to 24.5 dB/m at a spacing of 4 mm. He showed that the attenuation coefficient declined with a reduced slope as the slab spacing at the detection point increased. The study also showed that fracture geometry affects the transfer of sound energy .

CHAPTER 3

MATERIALS AND EQUIPMENT SPECIFICATION

3.1 Compressor

The compressor was used to provide the airflow required for the whistle to produce the sonic energy. The compressor used was a 1991 NAT'L BD make compressor with a Maximum Available Working Pressure (MAWP) of 200 psi at 450°F and is capable of providing the required flow rate of up to 7.5 SCFM (standard cubic feet minute). It is provided with a 0-200 psi pressure gauge to check the working pressure. The compressor outlet was fitted with a ½" female quick connect (Bootwala, 1999).

3.2 Sonic Generator – Whistle

The whistles used were purchased from Applied Ultrasonics, Bethel, Connecticut. Each whistle is about 3 inches long and is protected by two aluminum plates. The whistle is unidirectional (i.e., faces a single direction) and is therefore capable of directing the sonic energy produced into fractures. In the experimental run, each whistle was supported by a vertical stand coming up from the floor and was directed into the center of the artificially generated fracture. The manufacturer states that the whistles to have an intensity of about 160 dB at the source; however, preliminary tests have shown that the whistles are not actually able to achieve this level, but do produce values very close to the stated value 155dB. (Zarnetske, 2000)

This study estimates the sound intensity from the regression equation for Whistle No.5 at 1-inch from the source at an average of 160.7 dB for the four airflow rates.

3.3 Sound Recording Equipment

The equipment used for this experiment can be broken down into four different units which used in conjunction are capable of recording the data necessary for this experiment. The units are as follows:

- Microphone assembly
- Laptop computer
- Calibration of sound recording equipment
- Cool Edit 96– Wave-Recording Software

3.3.1 Microphone

A simple diagram of the microphone assembly with the laptop computer computer is shown in Figure 3.1 . The microphone, Etymotic Research Model No. ER-7C, is a clinical probe microphone system. It consists of a 3-inch soft silicone rubber probe with a six-foot cord and a small amplifier box with a built-in equalization and 94dB calibrator. The probe has a 0.95 mm OD, 0.5 mm ID and is 76 mm long. An additional 40-foot audio cable was used along with the six-foot cord provided by the manufacturer, to allow for a practical working length. A 30-foot audio cable was used to connect the preamplifier box to the line inlet of the laptop computer. The microphone can be calibrated using the built-in calibrator, which generates an intensity of 94 dB at 1kHz. The microphone gives an undistorted output of 126 dB in the 0 dB position and 140 dB in the 20 dB position on the preamplifier box. It has a noise level of 55 dB in the 20 to 20000 Hz bandwidths (Bootwala, 1999).

3.3.2 Laptop Computer

The selected laptop computer was a Dell Latitude Xpi P133ST with a 133 MHz processor, a 540 MB hard drive, 16 MB RAM memory and a sound card, which was a minimum requirement in this study. The wave analyzer software Cool Edit 96 was installed to examine the wave recorded by the microphone. (Jay,2000)

3.3.3. Calibration

Calibration was executed by inserting the microphone filament into the calibration chamber provided in the preamplifier box and keeping the on/off switch lowered. The reading was read off the scale on the wave analyzer software. This was a negative axis scale with units in decibels starting from zero. The reading obtained was a relative number and has a negative value corresponding to the 94 dB calibration tone. This relative value was added to the calibration tone 94 dB to get the reading corresponding to zero on the scale. This value was deemed the calibration value. Any sound intensity measurement taken was read off the wave analyzer software scale and was added to this calibration value. It is also necessary to add the absolute value of the recorded sound intensity taken from the software scale to the calibrated value, because the relative value is taken off a negative axis scale (Bootwala, 1999).

3.3.4 Cool Edit 96 – Wave Analyzer Software

The program used, Cool Edit 96, is a digital audio editor for Windows 95 and Windows NT. It is a recorder, editor, and player of sound. In this research, it was used to analyzes the sound wave and can display the frequency variation and the average intensity of the sound wave recorded. The program requires an computer system with:

- Windows 95(or greater) or Windows NT
- 486 or better CPU
- 8 MB RAM
- 4 MB available hard drive space
- A stereo sound card (Zarnetske, 2000)

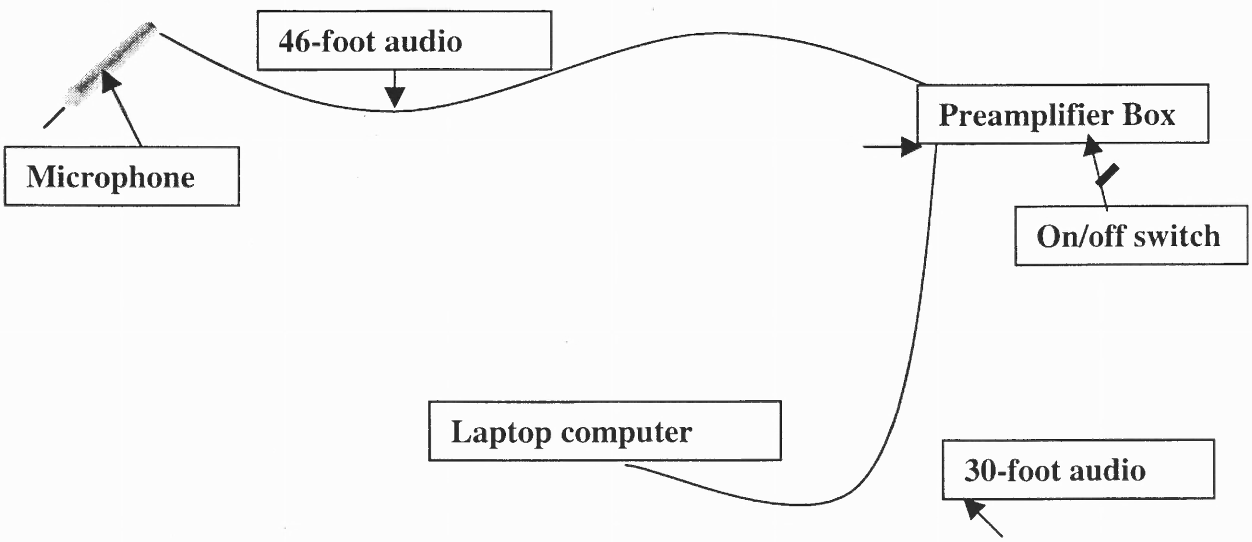

Figure 3.1 Illustration of sound recording system.

The above is the equipment which we used for recording Sound Intensity .

3.4 Field Study, Site Description and Well Layout.

The field study will be conducted in Derelco site, at Hillsborough, N.J., which is contaminated with trichloroethylene (TCE) and dichloroethylene (DCE). The complete description about the site, geology, previous well layouts is given by Bootwala, 2000 and Kaleem, 1999.But Mclaren hart Environmental engineers has developed new boreholes for removal of contaminants. The layout shown in figure 3.2 is referenced relativeto the previous borehole No.8. The present study is focused on between well number 3, 6, 7 as shown in the layout. The fracture at 25 ft down the earth will be used for experiments

.

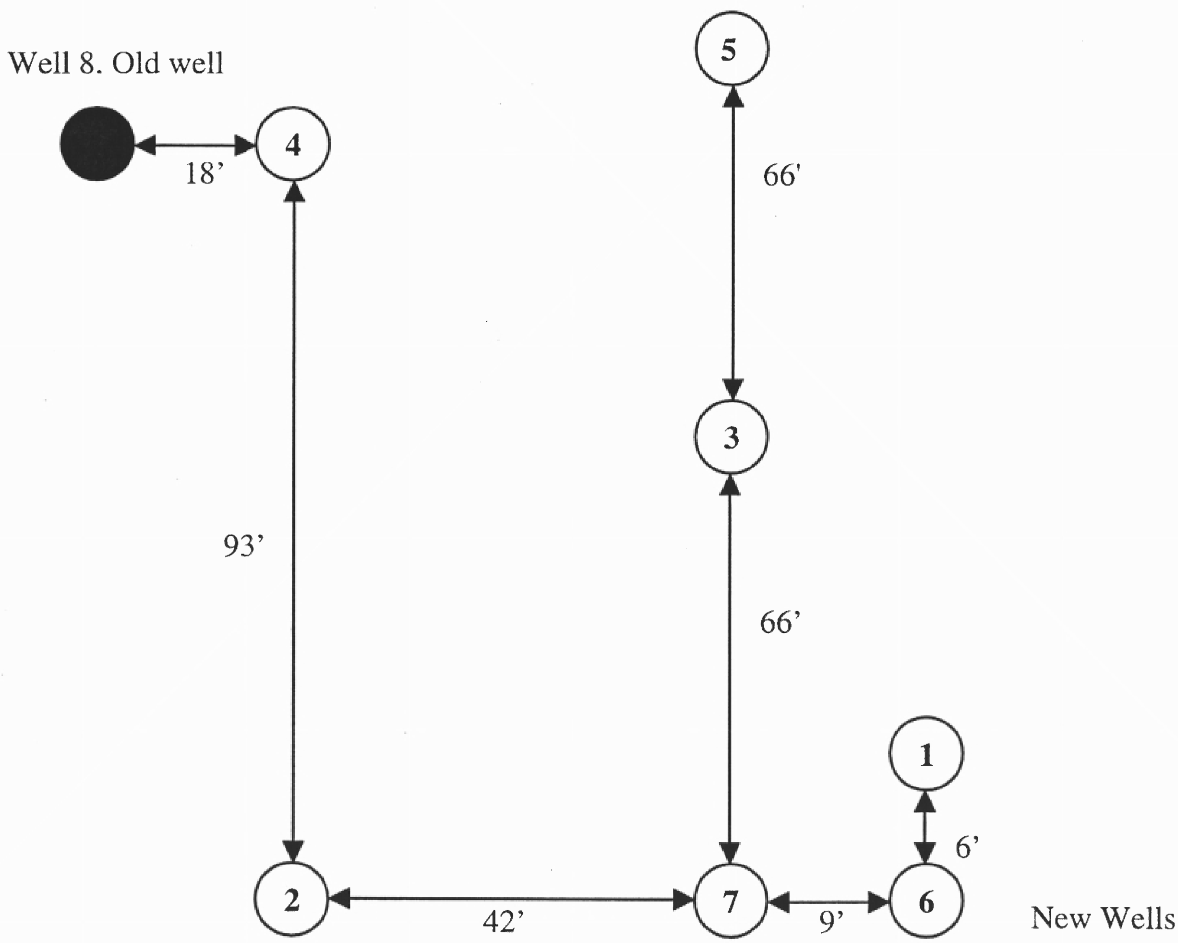

Figure 3.2 Shows the approximate location of new wells relative to Well No. 8 of previous boreholes. The well is shown in black show the previous Well No. 8

3.5 Equipment used for Field Experimental Runs

3.5.1 Compressor

The compressor provided the airflow needed to produce sonic energy generated by the whistle. The sonic energy and intensity of the whistle depends on the airflow through it. The compressor, which will be used, will be 19992 Ingersoll-Rand Industrial Air compressors Model No. T301080H with maximum available working pressure (MWAP) of 200 psi at 450 F capable of providing desired flow rates up to 10 SCFM (Bootwala, 2000)

3.5.2 Flow Manifold

The flow manifold arrangement, for the sonic field-test is demonstrated in Kaleem, 1999. The flow manifold is mounted on a rectangular board made from wood. The board is supported vertically by four stands that stand out at an angle of 30 degrees from the surface board. It consists of 4, 2/4 inch ID flow meters (2.4- 24.0) SCFM. Each flow meter is equipped with a ½ inch Sch. 40 Bronze Globe valve at the inlet and a ½ inch Sch. 40-IPS Forged brass Ball valve at the outlet .By means of these valves air can be made to travel through the desired flow meters. We need only one flow meter of these in the present study. These flow meters are connected on a single line, at the inlet, by means of four 1-inch Sch.40 Steel Tees, seven nipples and three tubing unions (1 inch Sch. 40). This single inlet line is connected to a compressor for airflow.

3.5.3 Packers

The sonic system will be coupled with two, four-foot packers to isolate and prevent air leakage from the sonic zone. These packers will be placed before and after the sonic generators in the borehole to isolate the treatment zone. The packers have external tubing through which an external nitrogen or air source can be used to inflate them as required.

3.5.4 Sonic Generator – Whistle No. 5 and Sound Recording Equipment

Whistle No. 5 was proved to be the best whistle and details about it has already been explained in section 3.2. Section 3.3 explains details about the sound recording equipment, which has been used for the field study.

3.5.5 Recommended Experimental set-up and Methodology

The basic methodology used for attenuation studies is same as used by Bootwala.The process diagram is shown in Figure 3.3 for the Bootwala studies. The present study also use the same methodology except the tip of microphone pointing toward the Sonic generator as recommended by previous studies. Figure 3.4 demonstrates the way microphone to be placed for recording results.

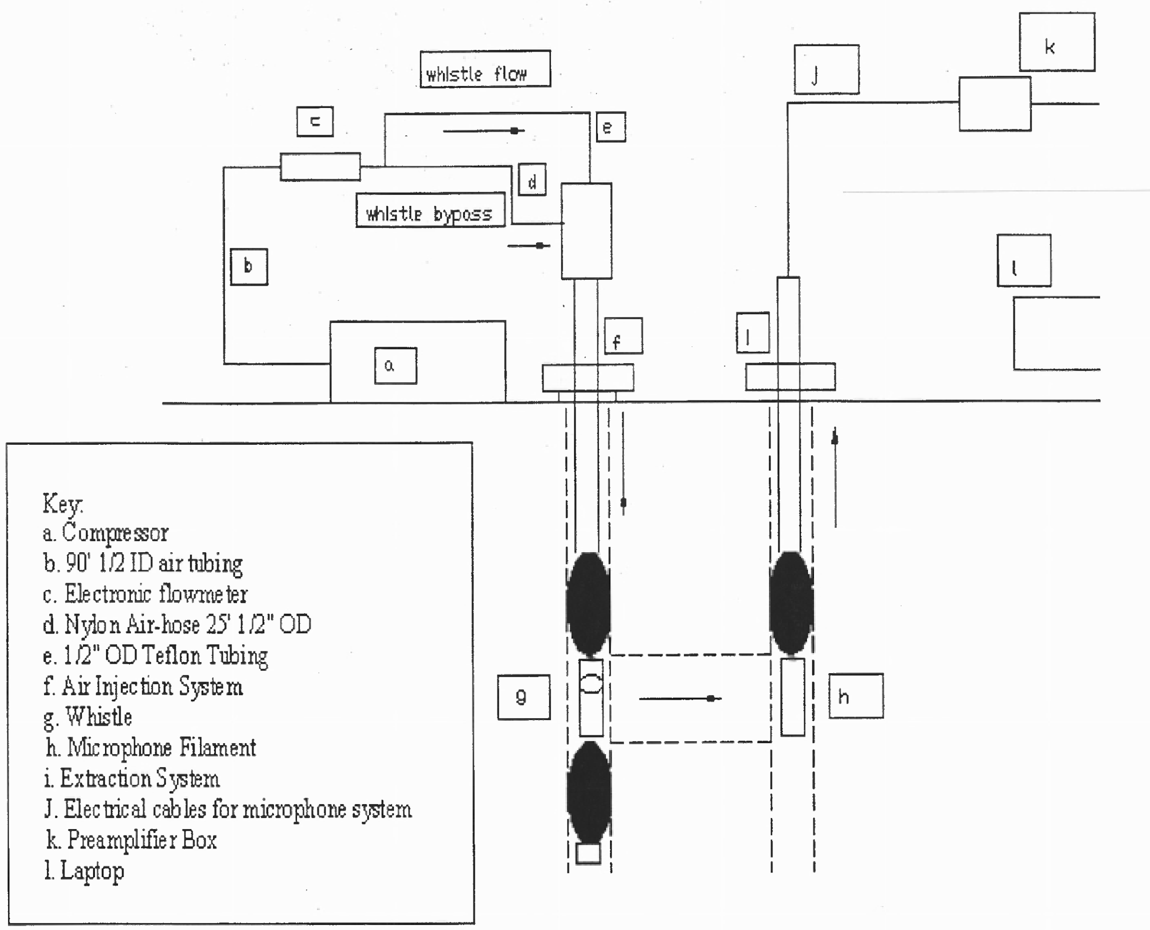

Figure 3.3 Field Experimental Setup for Measurement of Base
Bootwala, 2000

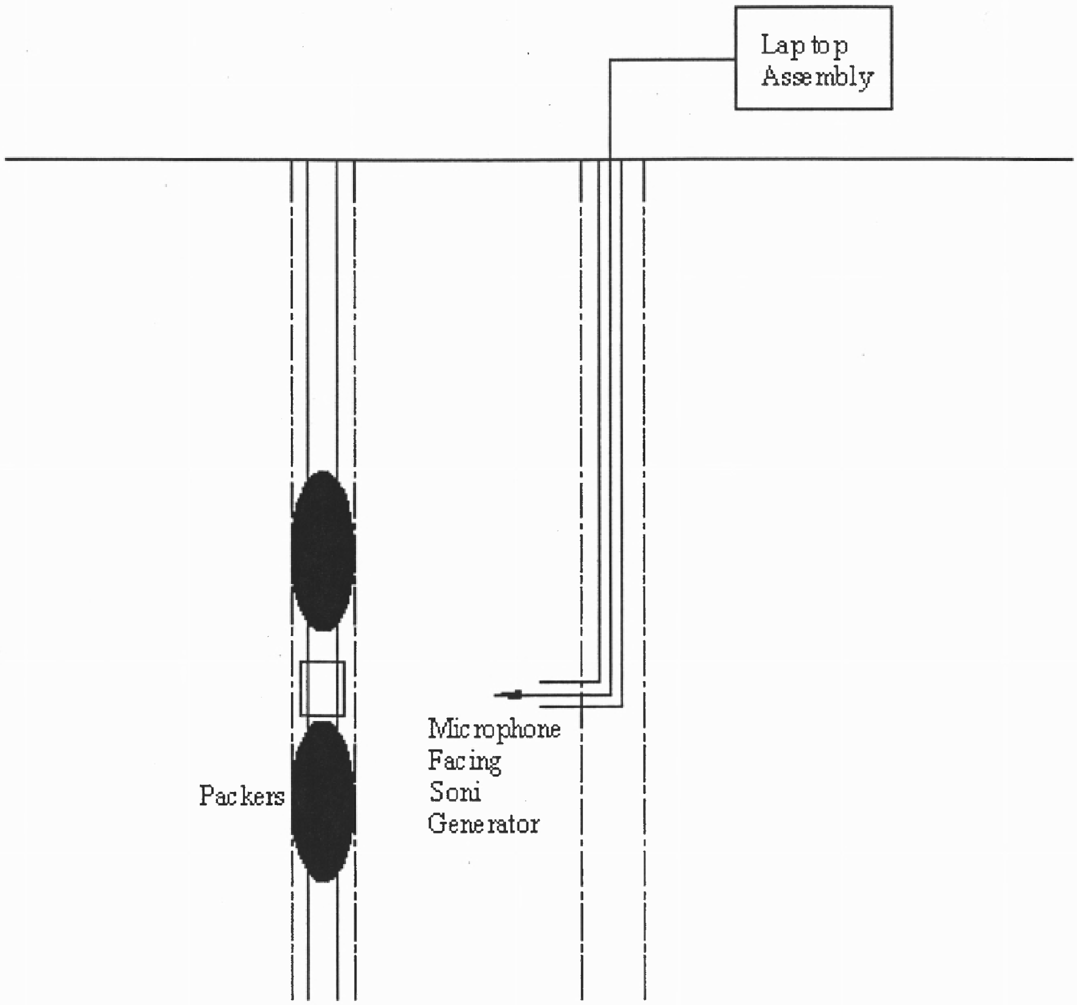

Fig. 3.4 Recommended Setup to be used for attenuation measurement study with microphone tip facing the sonic generator

CHAPTER 4

EXPERIMENTAL APPROACH AND RESULTS

4.1.Experimental Layout for Laboratory Tests

The laboratory experiments were aimed for finding the best whistle and the corresponding conditions, which we can use in field tests for further experimentation. The experimental layout of the equipment used was relatively simple and consistent throughout the tests for all whistles. This procedure is similar to one demonstrated in Zarnetske's study and Godde's study. The whistle assembly was mounted on a stand, and centered facing the tip of the sensor of microphone. The tubing was connected from the compressor to the whistle, and air was passed from the compressor through tubing into whistle, creating a sound source. Airflow rates were varied from 6.0-7.5 SCFM such as at 6.0, 6.5, 7.0, 7.5 SCFM respectively. Sound Intensity was measured at distance of 12, 6, 3, 1.5, 0.75 ft from the center of whistle tip using the microphone laptop assembly as shown by Figure 3.1.

4.1.1 Experiment Run 1 with Whistle No. 1.

The first experiment was performed using Whistle No. 1 as source of sonic energy. To verify the range of readings given correctly by the Lap Top Assembly, a sound meter was also used to record sound intensity. The values that were used for analysis purposes were the intensities recorded by the Lap Top assembly, as it is more precise. Table 4.1 shows data for intensity measurement (in dB) with distance at 12, 6, 3, 1.5 ft from whistle assembly for each of flow rates from 6-7.5 SCFM . Here the readings for distance of

0.75 ft are ignored, as they don't correspond to good data. Figure A.1- A5 shows graphs, which shows the variation of sound intensity with distance for each of the flow rates. The discussion will be presented in Chapter 5.

Distance (ft)	Sound Intensity (dB) (6.0 SCFM)	Sound Intensity (dB) (6.5 SCFM)	Sound Intensity (dB) (7.0 SCFM)	Sound Intensity (dB) (7.5 SCFM)
12	96.08	99.06	101.06	107.17
6	100.8	103	104.75	114.8
3	104.01	107.1	107.29	120.08
1.5	108.99	110.3	111.94	123.38

TABLE 4.1 Showing variation of Sound Intensity for Whistle No. 1 with distance at flow rates of 6.0 SCFM, 6.5 SCFM, 7.0 SCFM and 7.5 SCFM respectively.

4.1.2 Experiment 2 with Whistle No. 2.

The second Experiment was performed using Whistle No. 2 as sonic generator. The same experimental methodology was applied as for Whistle No. 1. The values which we used for analysis purpose are those of laptop assembly as it is more precise. Table 4.2 shows data for intensity measurement (in dB) with distance at 12, 6, 3, 1.5 and .75 ft from the center of whistle assembly for each of flow rates from 6-7.5 SCFM. Figure A6 – A10 show graphs, which shows the variation of sound intensity with distance for each of the flow rates. The discussion will be presented in Chapter 5.

Distance (ft)	Sound Intensity (dB) (6.0 SCFM)	Sound Intensity (dB) (6.5 SCFM)	Sound Intensity (dB) (7.0 SCFM)	Sound Intensity (dB) (7.5 SCFM)
12	116.15	117.14	118.63	118.49
6	120.43	121.84	123.4	122.32
3	123.61	128.24	126.78	126.62
1.5	128.45	132.04	135.07	137.31
0.75	132.94	138.59	140.45	140.95

TABLE 4.2 Showing variation of Sound Intensity for Whistle No. 2 with distance at flow rates of 6.0 SCFM, 6.5 SCFM, 7.0 SCFM and 7.5 SCFM respectively.

4.1.3 Experiment 3 with Whistle No. 3.

The third Experiment was performed using Whistle No. 3 as sonic generator. The same experimental methodology was applied as for Whistle No. 1. The values which we used for analysis purpose is that of laptop assembly as it is more precise. Table 4.3 shows data for intensity measurement (in dB) with distance at 12, 6, 3, 1.5 and .75 ft from center of whistle assembly for each of flow rates from 6-7.5 SCFM. Figure A11 – A15 shows graphs, which shows the variation of sound intensity with distance for each of the flow rates. The discussion will be presented in the next chapter.

Distance (ft)	Sound Intensity (dB) (6.0 SCFM)	Sound Intensity (dB) (6.5 SCFM)	Sound Intensity (dB) (7.0 SCFM)	Sound Intensity (dB) (7.5 SCFM)
12	103.34	106.57	108.7	108.46
6	111.86	114.29	119.34	116.2
3	115.74	118.14	122.71	122.03
1.5	118.84	123.14	131.79	129.64
0.75	126.64	130.64	134.04	135.64

TABLE 4.3 Showing variation of Sound Intensity for Whistle No. 3 with distance at flow rates of 6.0 SCFM, 6.5 SCFM, 7.0 SCFM and 7.5 SCFM respectively.

4.1.4 Experiment 4 with Whistle No. 4.

The fourth experiment was performed using Whistle No. 4 as sonic generator. The same experimental methodology was applied as for Whistle No. 1. The values which we used for analysis purpose is that of laptop assembly as it is more precise. Table 4.4 shows data for intensity measurement (in dB) with distance at 12, 6, 3, 1.5 and .75 ft from center of whistle assembly for each of flow rates from 6-7.5 SCFM. Figure A16 – A20 show graphs, which shows the variation of sound intensity with distance for each of the flow rates. The discussion will be presented in the next chapter.

Distance (ft)	Sound Intensity (dB) (6.0 SCFM)	Sound Intensity (dB) (6.5 SCFM)	Sound Intensity (dB) (7.0 SCFM)	Sound Intensity (dB) (7.5 SCFM)
12	116.88	118.22	117.93	118.1
6	120.44	120.84	121.54	121.64
3	125.81	125.87	127.44	127.01
1.5	130.6	132.4	132.04	131.94
0.75	136.3	138.94	137.84	136.8

TABLE 4.4 Showing variation of Sound Intensity for Whistle No. 4 with distance at flow rates of 6.0 SCFM, 6.5 SCFM, 7.0 SCFM and 7.5 SCFM respectively.

4.1.5 Experiment 5 with Whistle No.5

The fifth experiment was performed using Whistle No. 5 as sonic generator. The same experimental methodology was applied as for Whistle No. 1. The values which we used for analysis purpose is that of laptop assembly as it is more precise. Table 4.5 shows data for intensity measurement (in dB) with distance at 12, 6, 3, 1.5 and .75 ft from center of whistle assembly for each of flow rates from 6-7.5 SCFM. Figure A21 – A25 shows graphs, which shows the variation of sound intensity with distance for each of the flow rates. The discussion will be presented in the next chapter.

Distance (ft)	Sound Intensity (dB) (6.0 SCFM)	Sound Intensity (dB) (6.5 SCFM)	Sound Intensity (dB) (7.0 SCFM)	Sound Intensity (dB) (7.5 SCFM)
12	117.05	116.26	117.61	118.41
6	120.45	120.44	120.97	124.69
3	126.34	125.14	127.74	131.54
1.5	132.04	132.64	132.7	136.84
0.75	139.34	139.34	140.11	140.54

TABLE 4.5 Showing variation of Sound Intensity for Whistle No. 5 with distance at flow rates of 6.0 SCFM, 6.5 SCFM, 7.0 SCFM and 7.5 SCFM respectively.

4.2 Experiments with Combined Whistle Assembly.

4.2.1 Experimental Layout

The experimental layout is almost the same as that used for tests in Section 4.1 except here two whistles are mounted on a stand with Whistle No. 5 in the center and Whistle No. 4 rotating at angles from 45, 90, 135, 180, 225, 270, 315, 360 from the tip of Whistle No.5 at constant radius of 7 inches as shown in Figure 4.1.

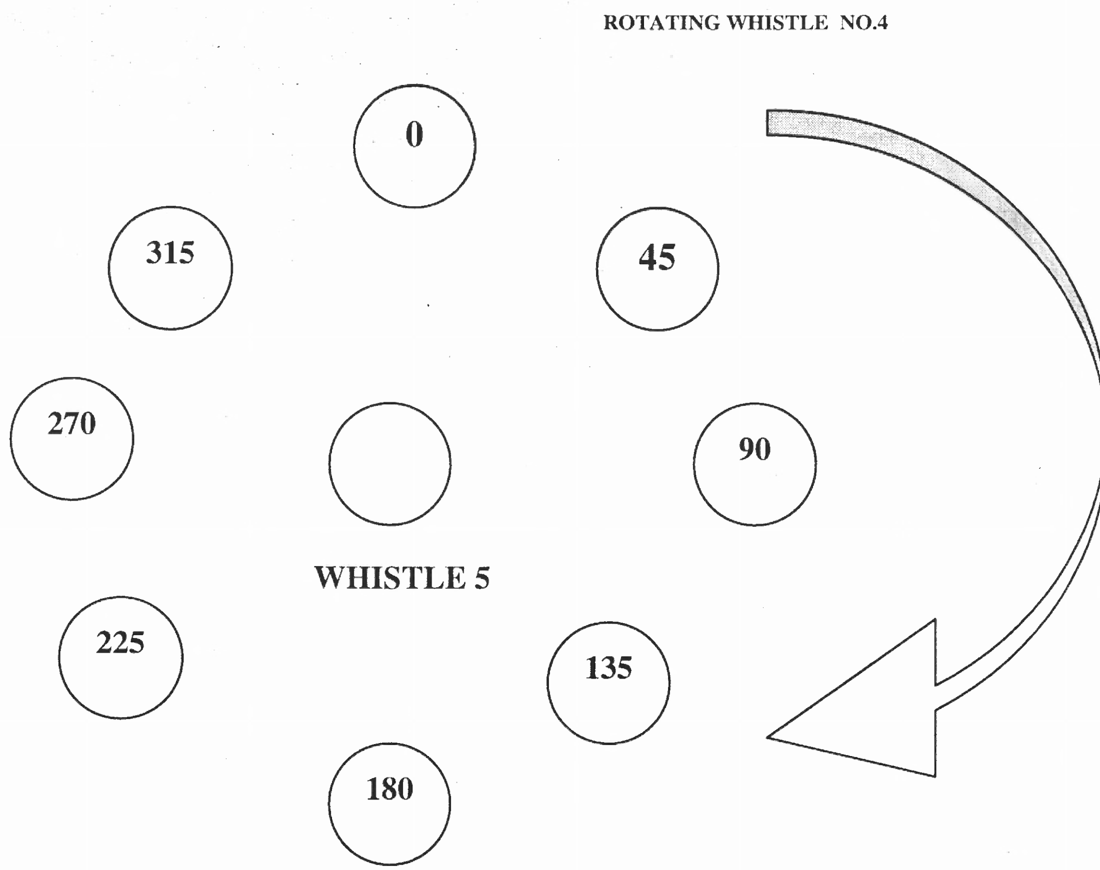

Figure 4.1 shows the arrangement of combined whistle assembly. Whistle No.5 is at center and Whistle No.4 is rotated at different angles as shown in the figure.

4.2.2 Experimental Runs 6-13 With Rotation of Whistle No. 4 at Angle of 45, 90, 135, 180, 225, 270 , 315, 360 From the Tip of Whistle No.5 at Constant Radius of 7 inches

The flow rate for the combined assembly is taken as the best for each of respective whistle, which we concluded from experiments in section 4.1. The flow rate for whistle No. 5 is taken at 7.5 SCFM and Whistle No. 4 taken at 6.0 SCFM. The arrangement is shown in figure 4.1 as shown. The observed experimental data for the above experiment is shown in Table 4.2.1.The table shows data for sound intensity with distance similar as that explained in section 4.1.

	Angle for Whistle No.4 relative to center of Whistle No.5							
Distance(ft)	Sound Intensity (dB)							
	360(0)	45	90	135	180	225	270	315
12	114.64	114.69	114.65	116.71	119.61	117.24	118.64	118.74
6	119.64	116.95	118.02	120.25	123.57	121.74	121.89	121.74
3	124.4	120.04	121.71	123.86	124.94	124.94	124.41	124.74
1.5	130.04	124.04	124.14	125.94	130.04	129.04	128.64	128.84
.75	134.04	129.08	133.21	128.99	133.43	132.04	134.06	134.14

Table 4.6 Sound Intensity as a function of distance and angel of rotation using Whistle No.4 and 5

The graphs showing best fit regression analysis curve for all whistles are attached in Figures A.26- A33. The results will be discussed in next chapter with reference to previous studies and extended discussion of study done so far.

CHAPTER 5

DISCUSSION OF EXPERIMENTAL RESULTS

5.1 Experimental Run 1-5.

The above runs were done to optimize the flow rate at which the whistle gives the maximum intensity to identify the best whistle that can be used for field studies. The results for this study have been documented in Chapter 4. A comparison with the Bootwala's studies and other studies has been made for analysis. The result obtained will decide the scenario for further study.

5.1.1 Results of Run 1.

In this run Whistle No.1 was used as described in section 4.1. Table 4.1 shows the calculated values of sound intensity with distance at flow rates from 6-7.5 SCFM are shown. From the table we can observe that as the distance is decreased the sound intensity increases which is as expected. The table shows that maximum observed intensity correspond to 7.5 SCFM flow rate at the distance of 1.5ft from the sonic generator to be 123 dB. Also it has been observed that there is an increase of about 4 decibels in sound intensity as we half the distance. The intensity increased as the flow rate increased at a specific distance from sonic generator. Figure A1 shows the plot for sound intensity with distance at 6.0 SCFM flow rate. The figure shows the fall in intensity as distance is increased which is expected. The regression analysis showed that the curve Power Equation (log-log) curve fit gives the highest correlation coefficient. Exponential curve fits were also attempted (as theory predicts) but the correlation coefficients were lower on all curves.. Similar behavior is observed for other flow rates from 6.5 SCFM, 7.0 SCFM and 7.5 SCFM as shown by figures from A2- A4. The Bootwala results are also shown in for Figure A1 and A2 for flow rates of 6.0 SCFM and 6.5 SCFM respectively. The data shown for Bootwala's study show higher intensities as compared to observed in the above study. These can be explained that there is some deformation in Whistle 1 during the period between the two studies. Whistle No.1 should be sent to manufacturer for maintenance. Also shown the Figure A.5 which shows the relative falls for different flow ratres demonstrating high values at flow rate of 7.5 SCFM .An analysis comparing theory and experimental results will be done later in this chapter.

5.1.2. Results of Run 2.

In this run Whistle No.2 was used as described in section 4.1.2. Table 4.2 shows the calculated values of sound intensity with distance at flow rates from 6-7.5 SCFM. From the table we can observe that as the distance is decreased the sound intensity increases which is as expected. But the intensities observed in above experiment are higher relative to Whistle No.1. The table shows that maximum observed intensity correspond to 7.5 SCFM flow rate at the distance of 0.75 ft from the sonic generator as to be 140.95 dB. Also for a flow rate of 6.5 SCFM it has been observed that intensity is highest to be 140.45 at the same distance. It has been observed that there is an increase of 4-5 decibels in sound intensity as we half the distance. The intensity increased as the flow rate increased at a specific distance from sonic generator. Also from Figure A.10 it can be seen that there is not much variation in intensities with increase in flow rates. Figure A6 shows the plot for sound intensity with distance at 6.0 SCFM flow rate. The figure shows the fall in intensity as distance is increased which is expected. The regression analysis showed that the curve Power Equation (log-log) curve fit gives the highest correlation coefficient. Exponential curve fits were also attempted (as theory predicts) but the correlation coefficients were lower on all curves. Similar behavior is observed for other flow rates from 6.5 SCFM, 7.0 SCFM and 7.5 SCFM. as shown by Figures from A7-A9. Figure A.10 shows the decrease in intensity for different flow rates demonstrating high values at flow rate of 7.5 SCFM .An analysis comparing theory and experimental results will be done later in this chapter.

5.1.3 Results of Run 3.

In this run Whistle No.3 was used as described in section 4.1.3 .Table 4.3 shows the calculated values of sound intensity with distance at flow rates from 6-7.5 SCFM . From the table we can observe that as the distance is decreased the sound intensity increases which is as expected. The table shows that maximum observed intensity correspond to 7.5 SCFM flow rate at the distance of .75ft from the sonic generator as to be 135.64 dB. It has also been observed a jump of increase in intensity as distance is decreased from 12ft to 6ft . However it has been previously observed that there is an increase of 4-5 decibels in sound intensity as we half the distance. The intensity increased as the flow rate increased at a specific distance from sonic generator. Figure A11 shows the plot for sound intensity with distance at 6.0 SCFM flow rate. The shows the fall in intensity as distance is increased which is expected. The regression analysis showed that the curve Power Equation (log-log) curve fit gives the highest correlation coefficient. Exponential curve fits were also attempted (as theory predicts) but the correlation coefficients were lower on all curves. Similar behavior is observed for other flow rates from 6.5 SCFM, 7.0 SCFM and 7.5 SCFM as shown by figures from A12- A14. The Bootwala results are also shown in for Figure A11 and A12 for flow rates of 6.0 SCFM and 6.5 SCFM respectively. The data shown for Bootwala's study show higher intensities as compared to observed in the above study. These can be explained that there is some deformation in Whistle 3 during the period between the two studies. So Whistle No.3 should be sent to manufacturer for maintenance. Also shown the Figure A.15 which shows the intensity falls for different flow rates demonstrating high values at flow rate of 7.5 SCFM .An analysis comparing theory and experimental results will be done later in this chapter.

5.1.4 Results of Run 4.

In this run Whistle No.4 was used as described in section 4.1.4 Table 4.4 shows the calculated values of sound intensity with distance at flow rates from 6-7.5 SCFM are shown. From the table we can observe that as the distance is decreased the sound intensity increases which is as expected. The table shows that maximum observed intensity correspond to 6.5 SCFM flow rate at the distance of .75ft from the sonic generator as to be 138.9 dB. Also it has been observed that there is an increase of 4-5 decibels in sound intensity as we half the distance. The intensity increased as the flow rate increased at a specific distance from sonic generator. Figure A16 shows the plot for sound intensity with distance at 6.0 SCFM flow rate. The shows the fall in intensity as distance is increased which is expected. The regression of the form Exponential (Semi log) best fit the above experimental curve. Similar behavior is observed for other flow rates from 6.5 SCFM, 7.0 SCFM and 7.5 SCFM, as shown by Figures A17- A19.In the case of Whistle No. 4, the best curve fit was obtained from using a Exponential relationship which gave the highest correlation coefficient, in accordance with the theory. There is no apparent reason for this change. It is recommended that further studies of attenuation of sound in air for small distances be made. Figure A.20, shows the relative, decrease in intensity for different flow rates demonstrating very close variations with flow rates .An analysis comparing theory and experimental results will be done later in this chapter.

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5.1.5 Results of Run 5.

In this run Whistle No.5 was used as described in section 4.1.5. Table 4.5 shows the calculated values of sound intensity with distance at flow rates from 6-7.5 SCFM . From the table we can observe that as the distance is decreased the sound intensity increases which is as expected. The table shows that maximum observed intensity correspond to 7.5 SCFM flow rate at the distance of .75ft from the sonic generator as to be 140.13 dB. Also it has been observed that there is an increase of 4-5 decibels in sound intensity as we half the distance. The intensity increased as the flow rate increased at a specific distance from sonic generator. Figure A21 shows the plot for sound intensity with distance at 6.0 SCFM flow rate. The shows the fall in intensity with distance which is expected. Similar behavior is observed for other flow rates from 6.5 SCFM, 7.0 SCFM and 7.5 SCFM. as shown by figures from A22- A24. Also shown the Figure A.25 which shows the relative falls for different flow rates demonstrating high values at flow rate of 7.5 SCFM an analysis comparing theory and experimental results will be done later in this chapter.

The above section will build on discussion from section 5.1.1- 5.1.5. Table 5.1 shows the calculated values for maximum intensities at 1-inch distance from the sound source using the regression equation observed from the curves for respective cases.

WHISTLE NO.	FLOW RATE (SCFM)	MAXIMUM INTENSITY(dB)
1	6	131.2
1	6.5	128.59
1	7.0	123.12
1	7.5	151.44
2	6.0	147.637
2	6.5	157.95
2	7.0	160.5
2	7.5	163.7
3	6.0	146.45
3	6.5	151.7
3	7.0	160.7
3	7.5	162.7
4	6.0	157.4
4	6.5	152.86
4	7.0	155.9
4	7.5	154.08
5	6.0	159.2
5	6.5	160.35
5	7.0	160.3
5	7.5	163.05

Table 5.1 Showing extrapolated calculated maximum intensity at 1 inch from whistle.

These results will be used as basis to determine which whistle is the best for further research. These data show that maximum Intensity is to be for Whistle No. 5 at flow rate of 7.5 SCFM so we will use the above in field tests and for further research.

These results will be used as basis to determine which whistle is the best for further research. These data show that maximum Intensity is to be for Whistle No. 5 at flow rate of 7.5 SCFM so we will use the above in field tests and for further research. Whistle No. 2 and No.4 are showing comparable results but Whistle No. 5 is considered to better from past experience so we will use this whistle for Combined Assembly tests.

5.2 Results for Runs from 6-13.

The above runs were conducted as demonstrated in section 4.2 for the combined whistle assembly. The purpose for the above runs is to determine if the combination of two-whistle assembly produce high sound intensities as compared to that of single whistle assembly. Figure A26 – A33 show the curves for the above runs. In this run Whistle No.4 and Whistle No.5 were used as described in Section 4.2 Table 4.6 shows the calculated values of sound intensity with distance at different geometrical positions as described in Chapter 4 . From the table we can observe that as the distance is decreased the sound intensity increases which is as expected. The table shows that the maximum observed intensity corresponds to 315 degrees position at the distance of .75ft from the sonic generator as to be 134.14 dB. But the observed change in intensity with change in geometry is negligible. These values are less compared to that we observed for the single whistle assembly as in case of Whistle No. 5. The lower intensity observed with two whistles compared to one maybe result of a decrease in intensity caused by overlapping waves generated from each whistle.

5.3 Comparison of Theory and Results

Measured data were curve fit using a Power (Log-Log) and a Exponential (Semi-log) relationships. Theory predicts that intensity decreases by a semi-logarithmic relationship. Also attempted was the relationship given by Barber, 1992 which is basically semi-logarithmic.

The logarithmic curve fit resulted in the highest correlation coefficients for most whistles and a logarithmic relationship was used in this study. It could be possible that the short distance involved in this study relative to much greater distances in attenuation studies.

5.4 Preparations For Field Study

Preparations were made to perform field studies to determine contaminant removal rate for extended lengths of time, to extend Kaleem's (1999) data and to perform attenuation studies to follow the recommendations of Zarnetske's study (2000) and Godde's study (2000). This latter study would augment the study made by Bootwala (2000).

In February 2000, it became clear that our technology transfer partner would file bankruptcy. The bankruptcy was filed and McLaren/Hart Environmental Engineers ceased to exist in New Jersey. The consequences of this bankruptcy severely delayed our field effort, since the field was no longer available for our use.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS\

The conclusions of this study are:

- It was concluded that Whistle No.5 gives the highest sound intensity of 140.54 dB at a distance of 0.75 ft the closest distance used for measurement at a air flow rate of 7.5 SCFM. When the regression equation is used and extrapolated to 1 inch of the Whistle , the sound intensity is about an average 160.7 dB for the four airflow rates, which is very close to the manufacturers value of 160 dB.
- The data of sound intensity in decibels versus distance in feet are best curve fit using the Power Equation.
- It was also concluded that a single whistle produces higher sound intensities in comparison to the combination of two whistles.

The recommendations of this study are:

- It is recommended to use Whistle No. 5 alone in the field to measure attenuation at the fractured siltstone at the field site, following Zarnetske's and Godde's procedure.
- The previous work by Zarnetske and Godde should be expanded to give more knowledge from controlled laboratory tests. The work should be expanded to include soil, in addition, to the porous rock slabs.
- It is recommended to make the extended contaminant removal studies to augment Kaleem's (1999) study, when the field is available.

- It is recommended to make the field sound attenuation studies to follow the work of Zarnetske (2000), Godde (2000) and Bootwala (2000).

APPENDIX A
FIGURES AND DIAGRAM

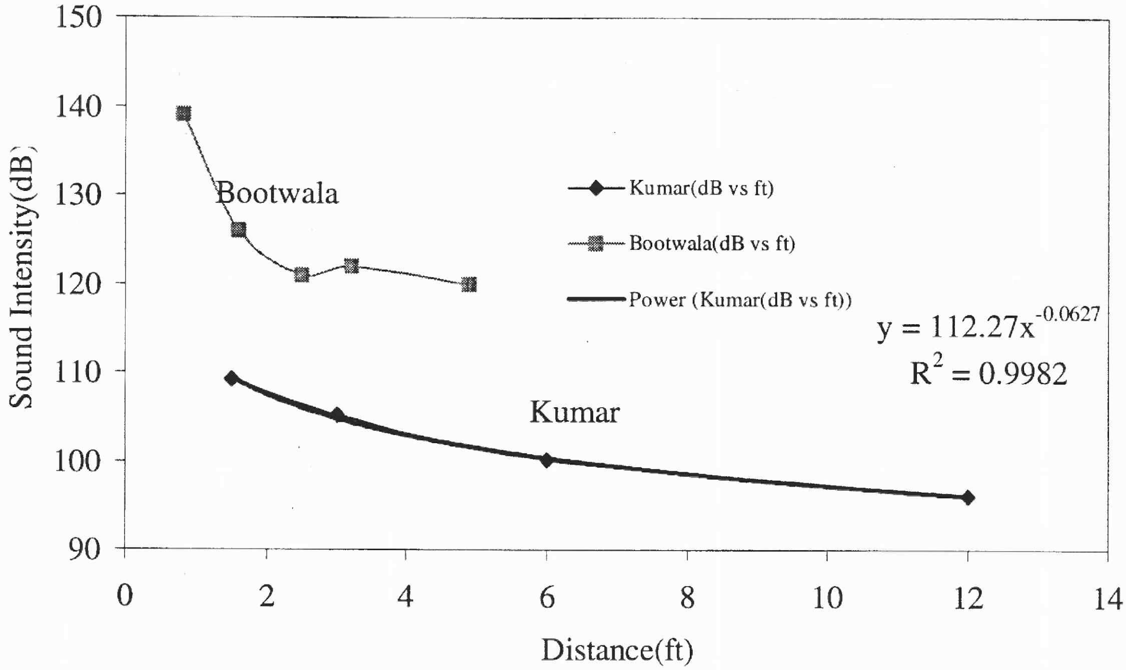


Figure A.1 Sound Intensity (dB) vs. Distance (ft) for Whistle No. 1at 6.0-SCFM airflow. Bootwala data is also shown in above

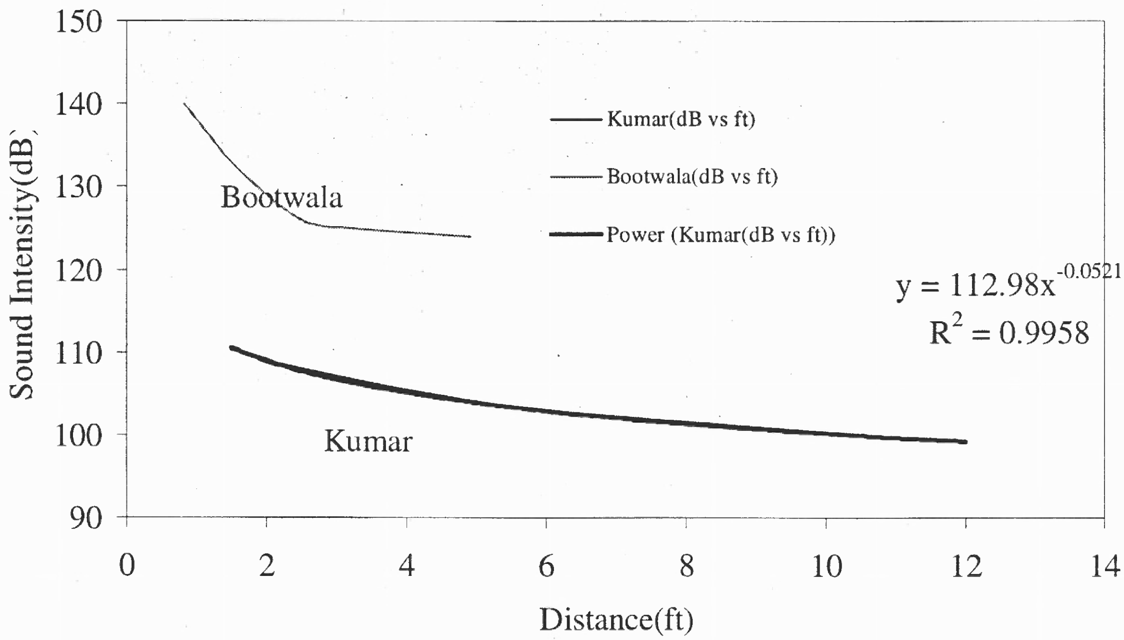


Figure A.2 Sound Intensity (dB) vs. Distance (ft) for Whistle No. 1at 6.5-SCFM airflow. Bootwala data is also shown in above.

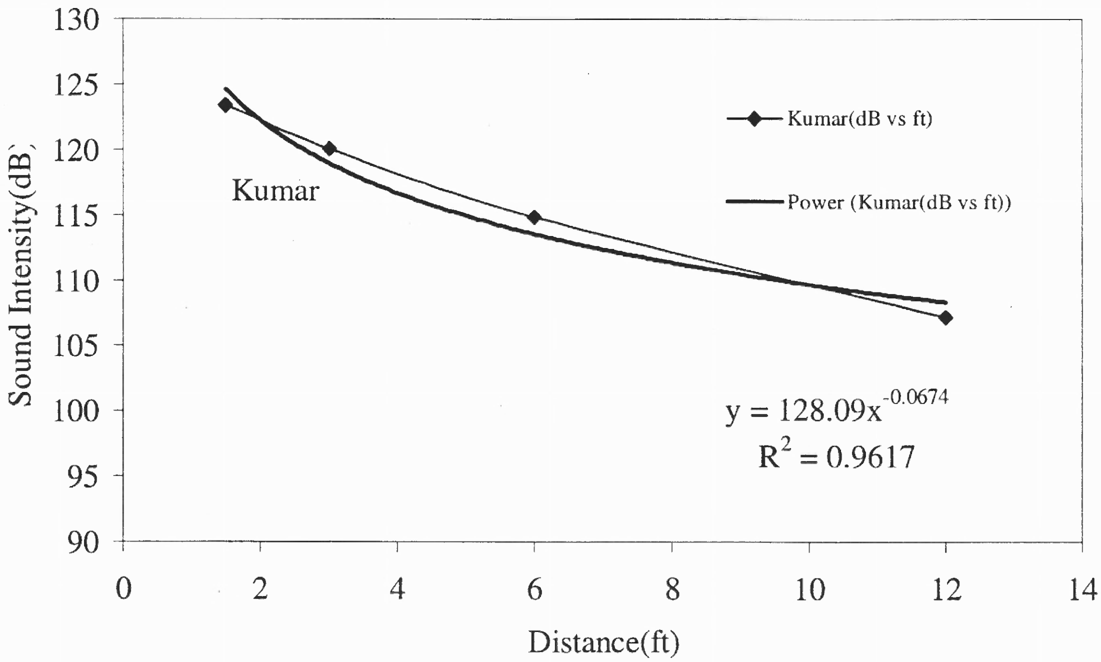


Figure A.3 Sound Intensity (dB) vs. Distance (ft) for Whistle No. 1at 7.0-SCFM Bootwala data is also shown in above.

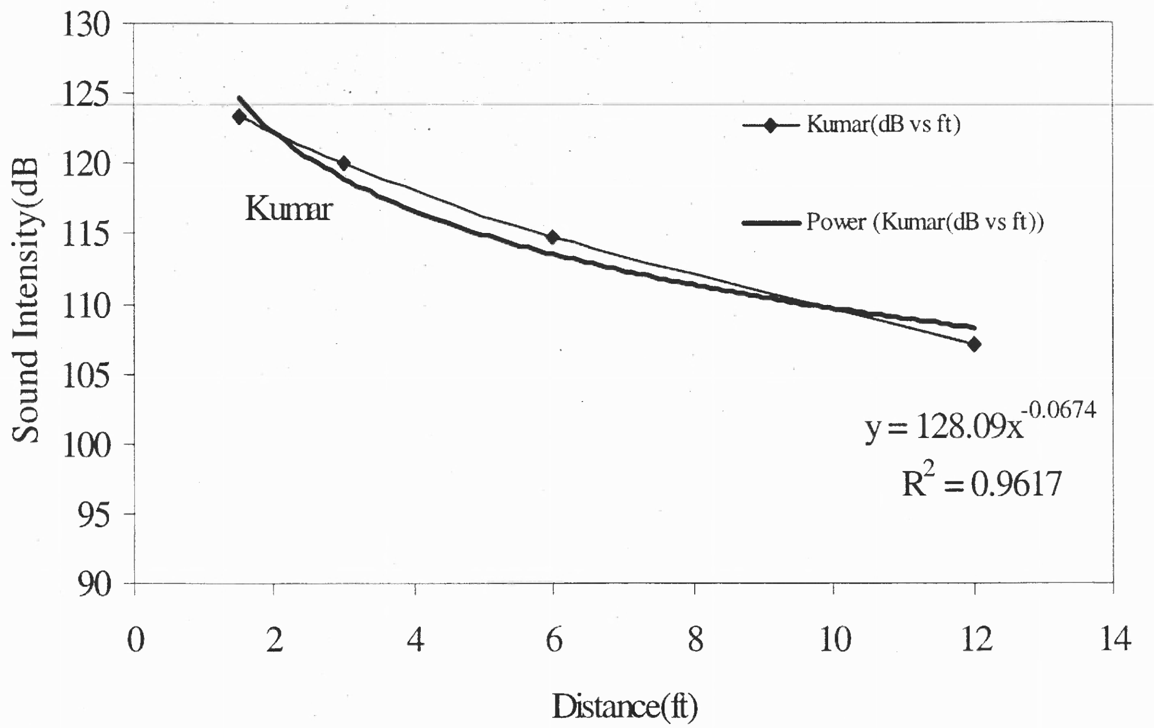


Figure A.4 Sound Intensity (dB) vs. Distance (ft) for Whistle No. 1at 7.0-SCFM airflow.

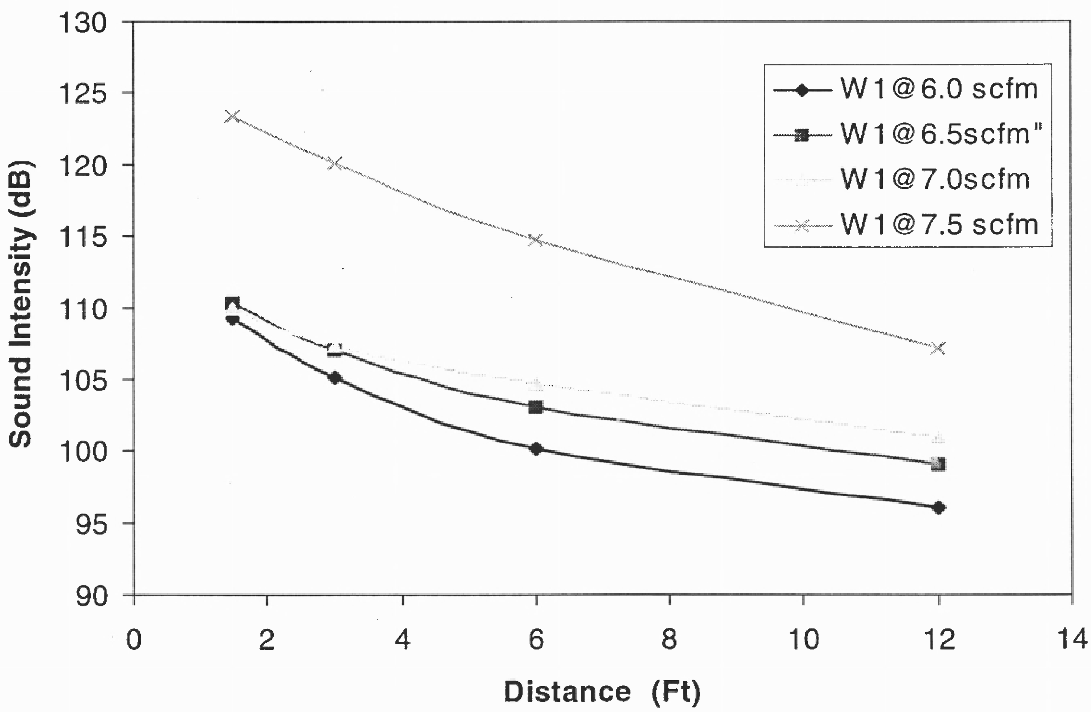


Figure A.5 Plot of Sound Intensity (dB) vs. Distance (ft) for Whistle No. 1 at 6.0-7.5 SCFM all in one graph.

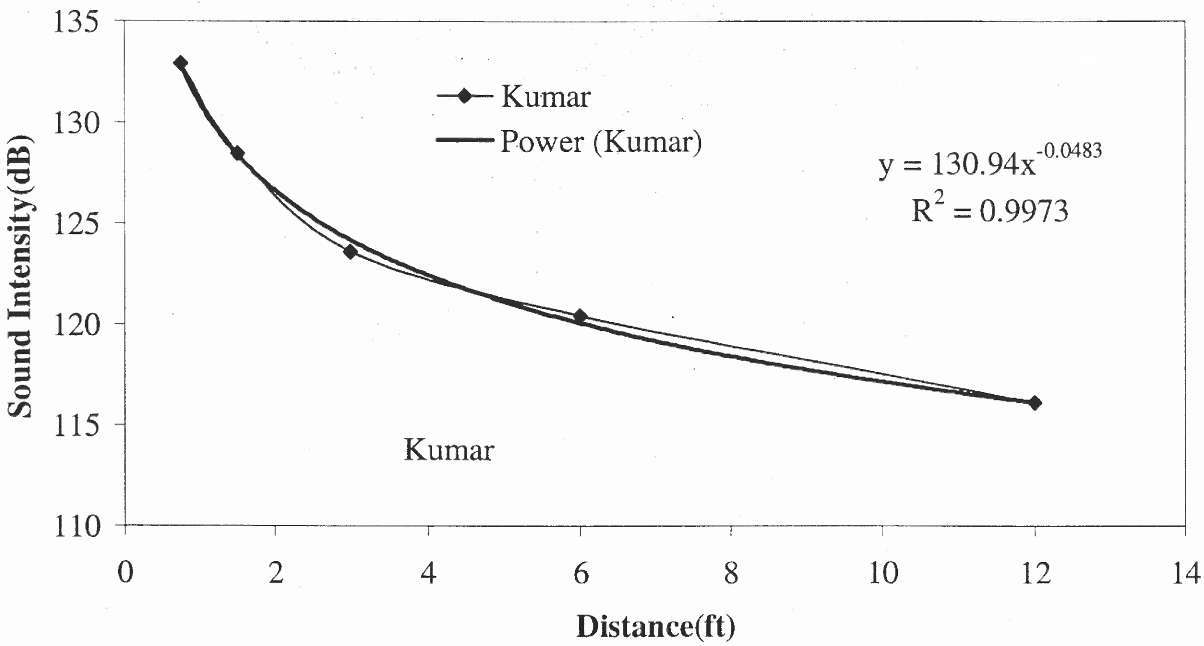


Figure A.6 Sound Intensity (dB) vs. Distance (ft) for Whistle No. 2at 6.0-SCFM airflow.

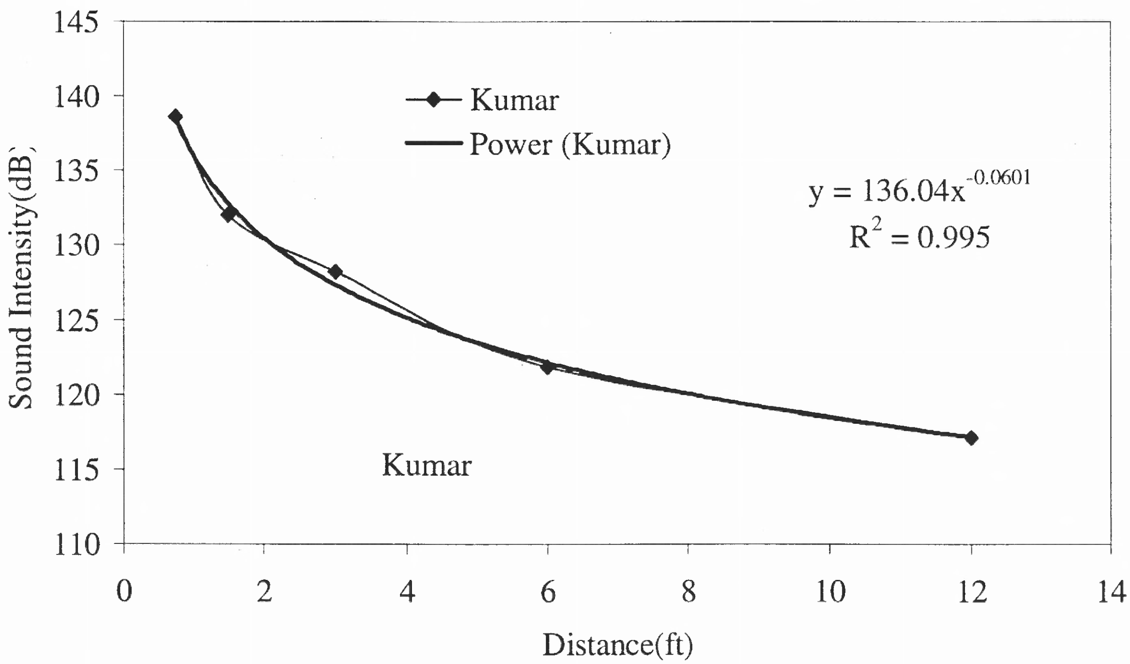


Figure A.7 Sound Intensity (dB) vs. Distance (ft) for Whistle No. 2at 6.5-SCFM airflow.

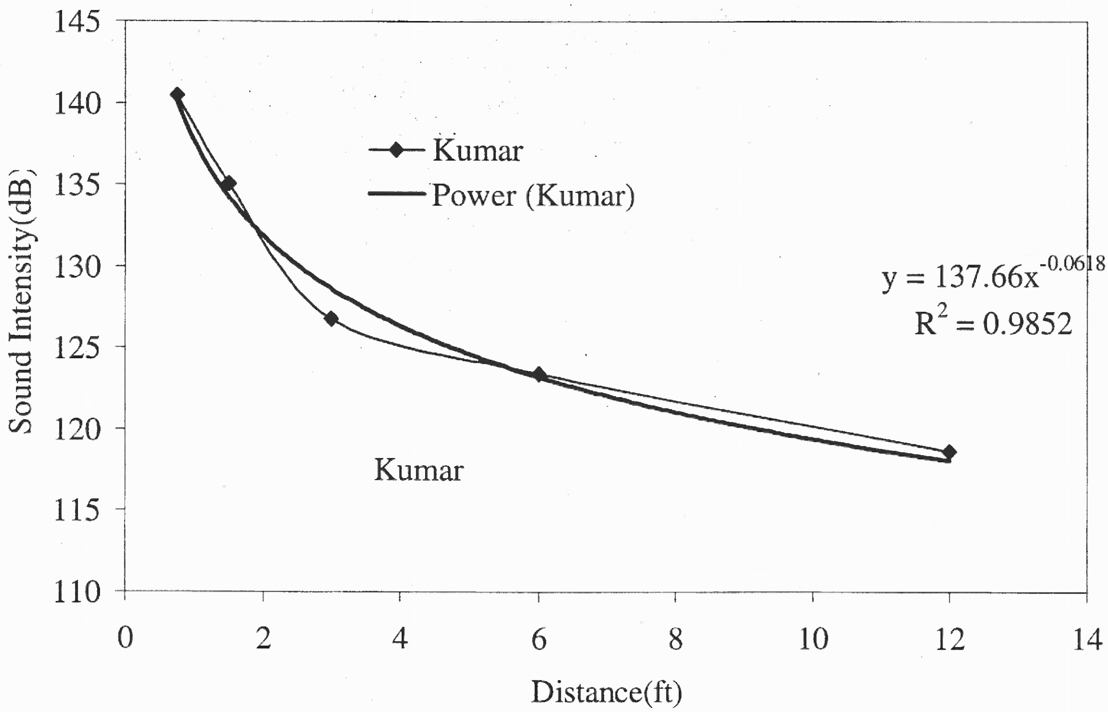


Figure A.8 Sound Intensity (dB) vs. Distance (ft) for Whistle No. 2 at 7.0-SCFM airflow.

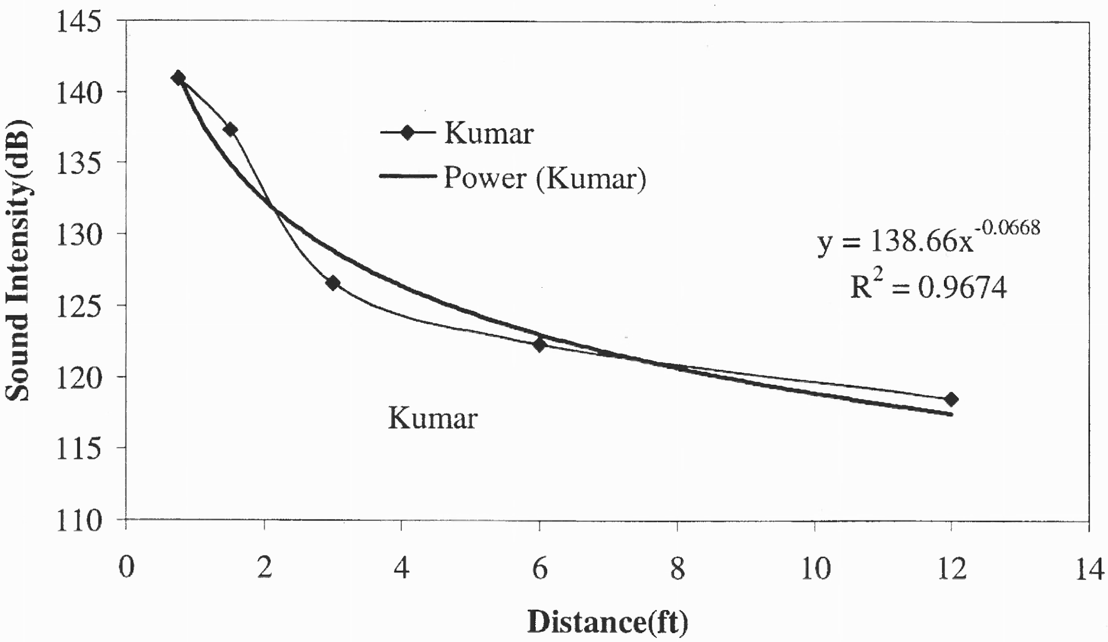


Figure A.9 Sound Intensity (dB) vs. Distance (ft) for Whistle No. 2at 7.5-SCFM airflow

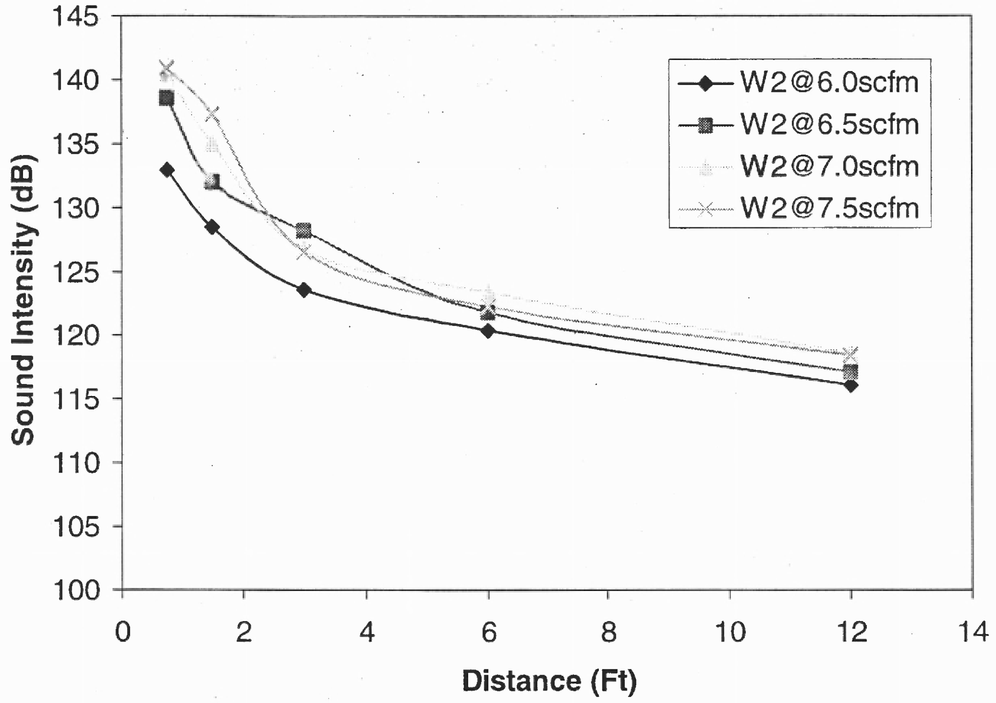


Figure A.10 Plot of Sound Intensity (dB) vs. Distance (ft) for Whistle No.2 at 6.0-7.5 SCFM all in one graph

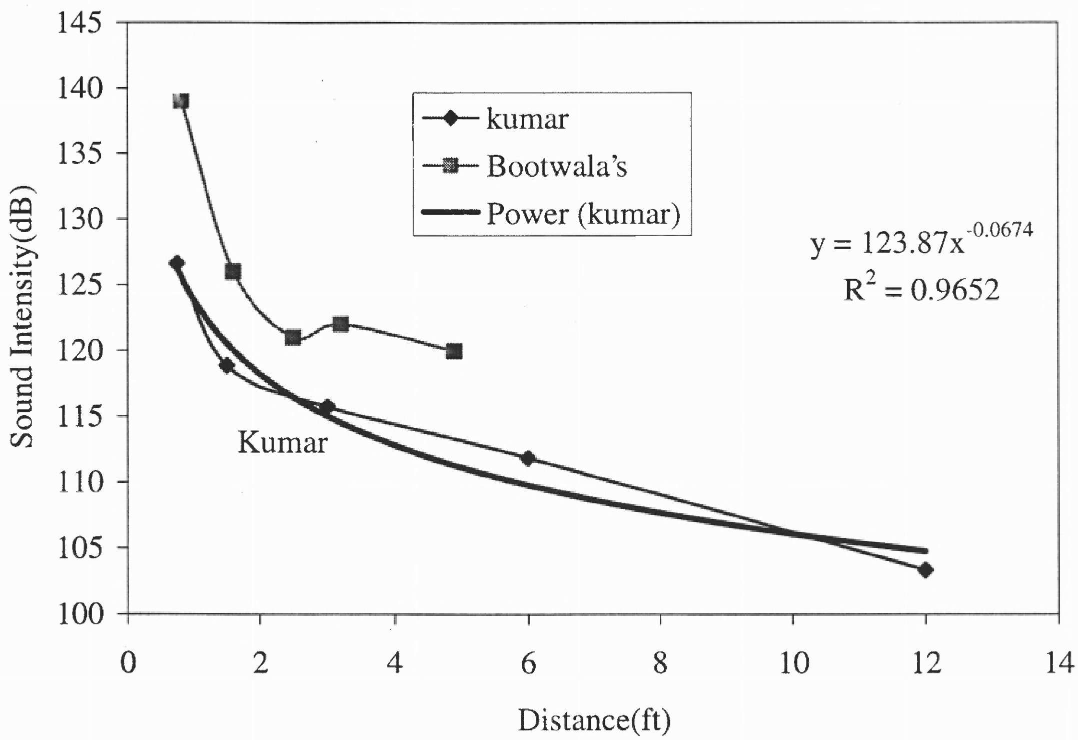


Figure A.11 Sound Intensity (dB) vs. Distance (ft) for No.3 Whistle at 6.0-SCFM. Bootwala data is also shown as marked.

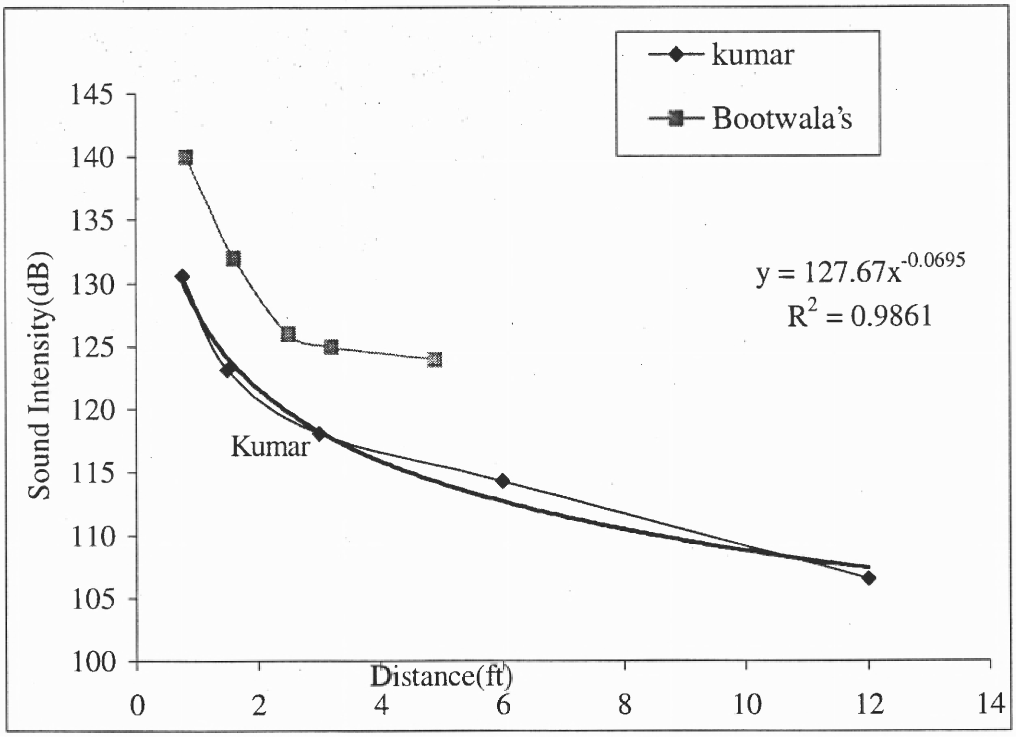


Figure A.12 Sound Intensity (dB) vs. Distance (ft) for No.3 Whistle at 6.5-SCFM . Also shown Bootwala curve.

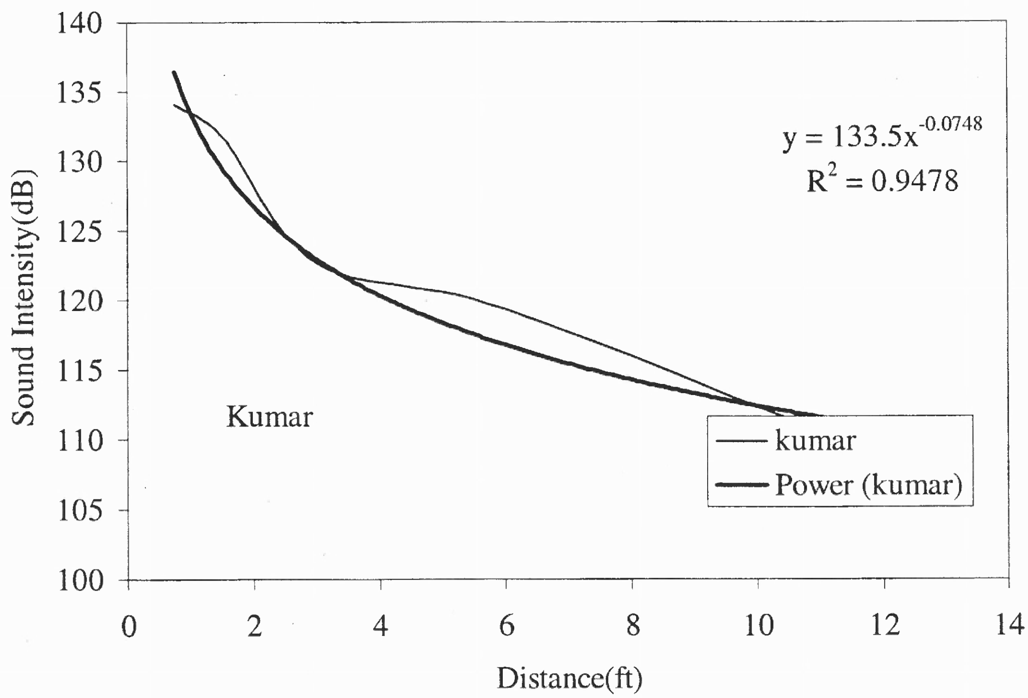


Figure A.13 Sound Intensity (dB) vs. Distance (ft) for No.3 Whistle at 7.0-SCFM airflow.

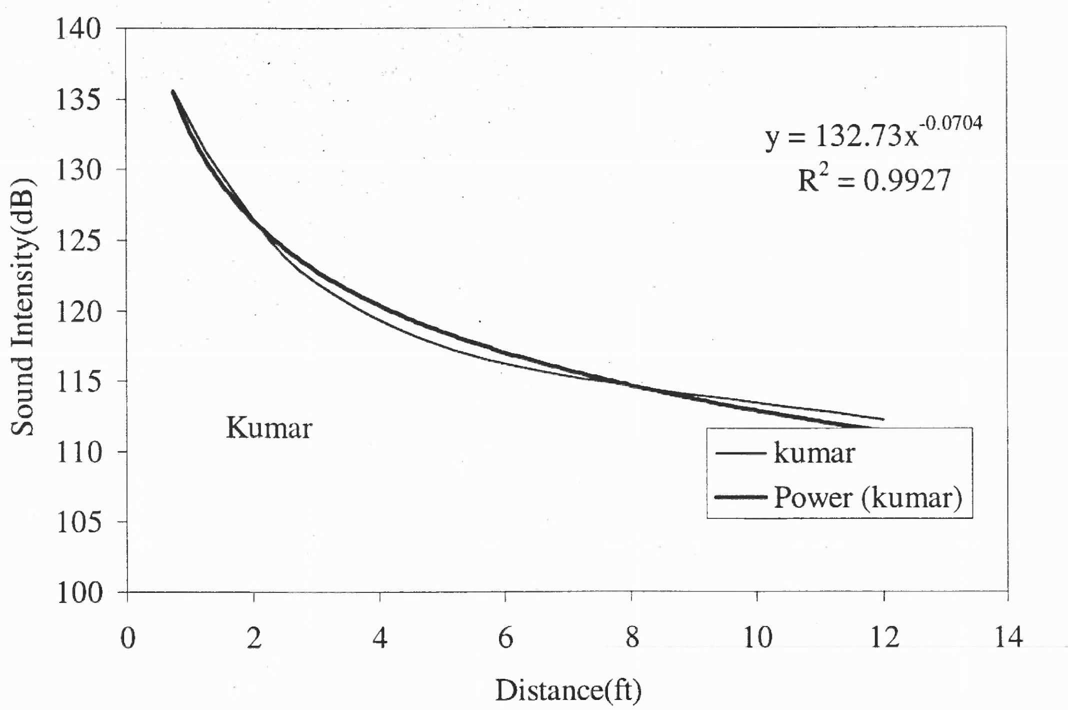


Figure A.14 Sound Intensity (dB) vs. Distance (ft) for No.3 Whistle at 7.5 SCFM airflow.

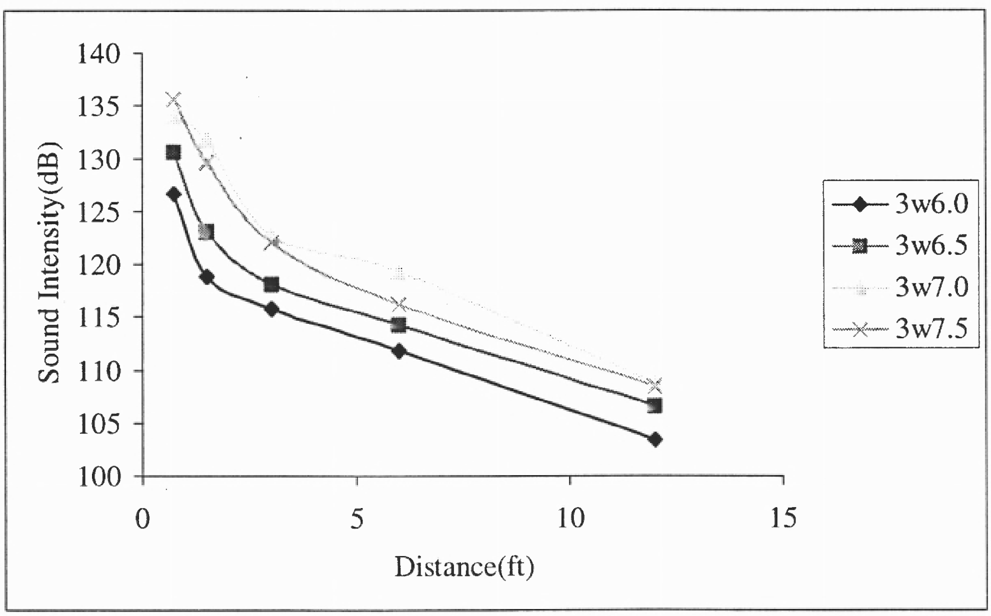


Figure A.15 Plot of Sound Intensity (dB) vs. Distance (ft) for No.3 Whistle at 6.0-7.5 SCFM all in one graph

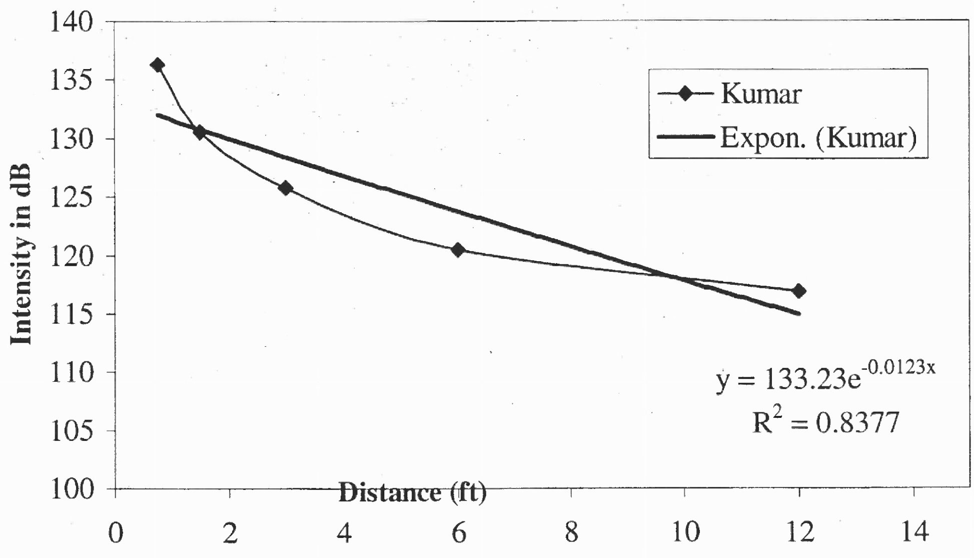


Figure A.16 Plot of Sound Intensity (dB) vs. Distance (ft) for No.4 Whistle at 6.0 SCFM

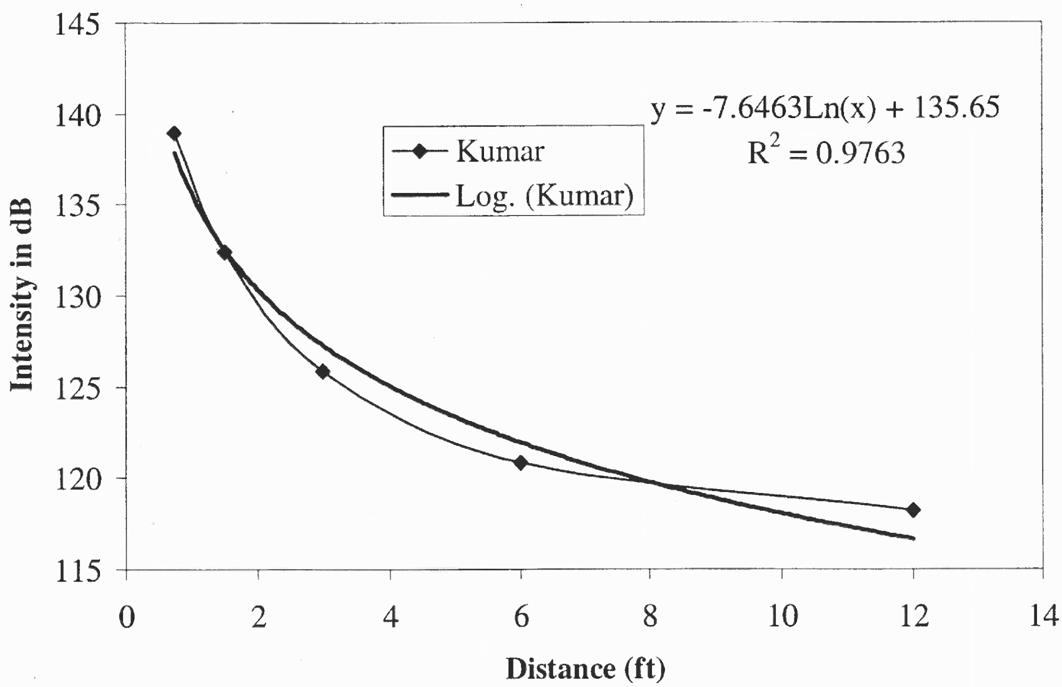


Figure A.17 Plot of Sound Intensity (dB) vs. Distance (ft) for No.4 Whistle at 6.5 SCFM

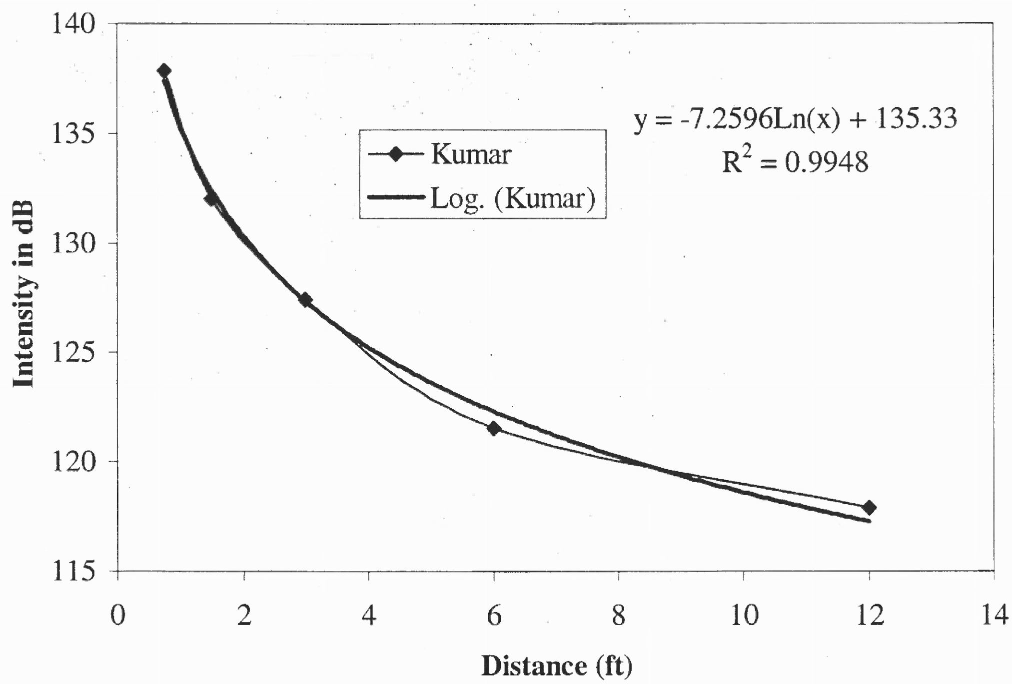


Figure A.18 Plot of Sound Intensity (dB) vs. Distance (ft) for No.4 Whistle at 7.0 SCFM

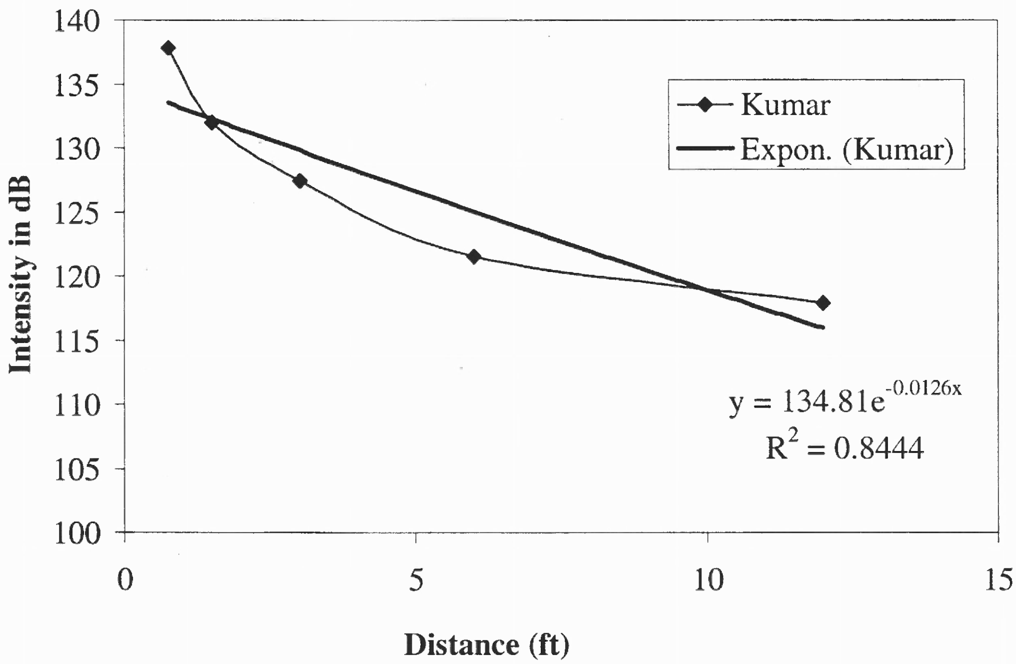


Figure A.19 Plot of Sound Intensity (dB) vs. Distance (ft) for No.4 Whistle at 7.5 SCFM

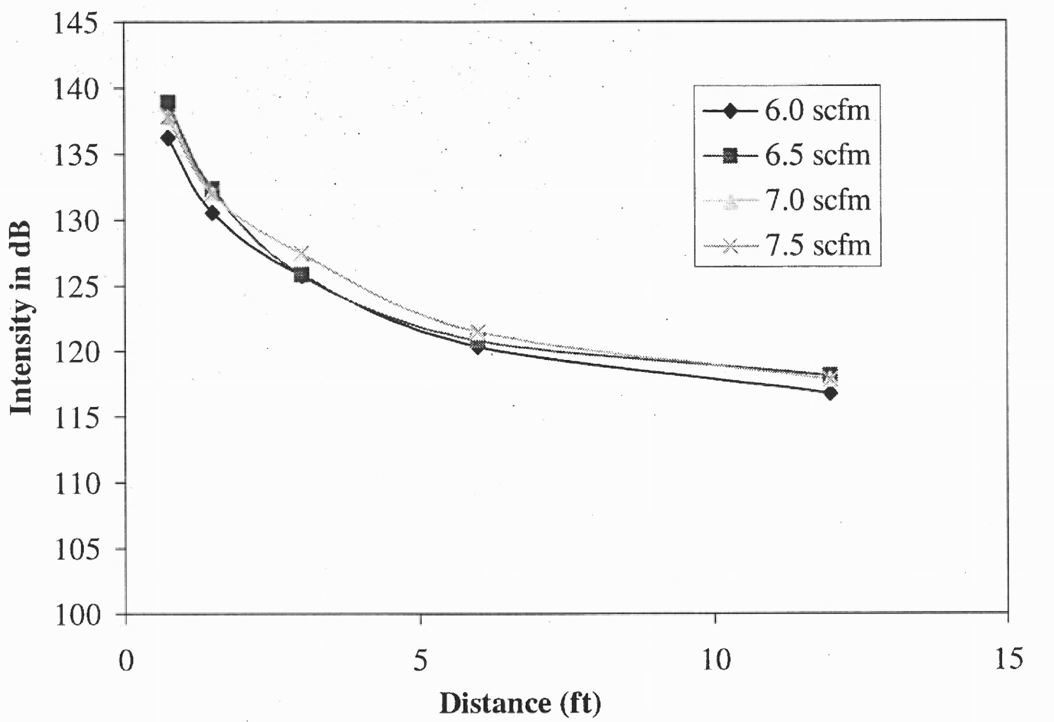


Figure A.20 Plot of Sound Intensity (dB) vs. Distance (ft) for No.4 Whistle at 6.0-7.5 SCFM all in one graph

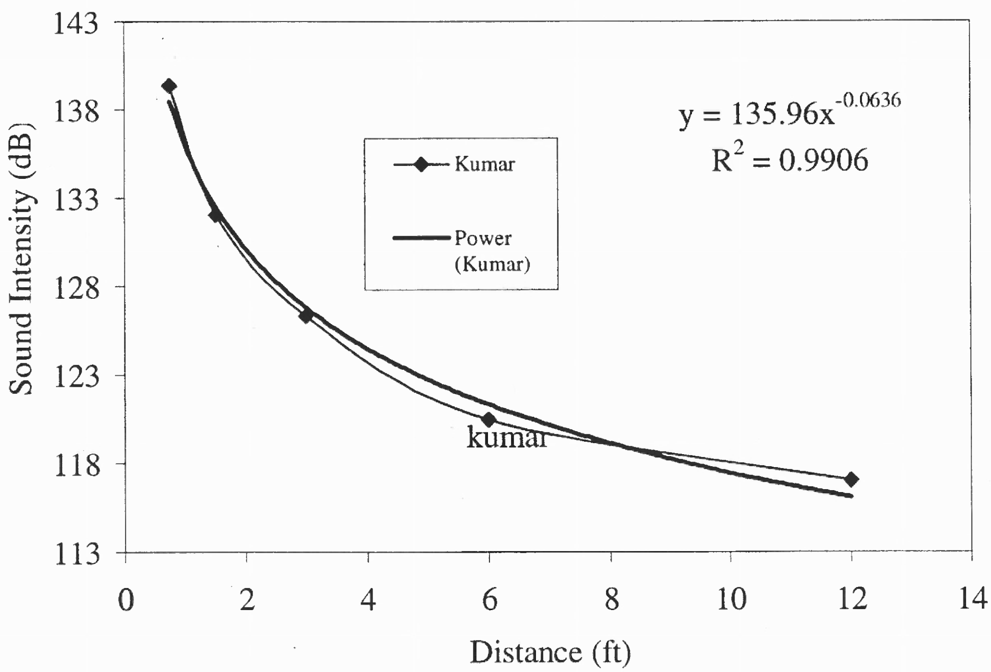


Figure A.21 Plot of Sound Intensity (dB) vs. Distance (ft) for No.5 Whistle at 6.0 SCFM

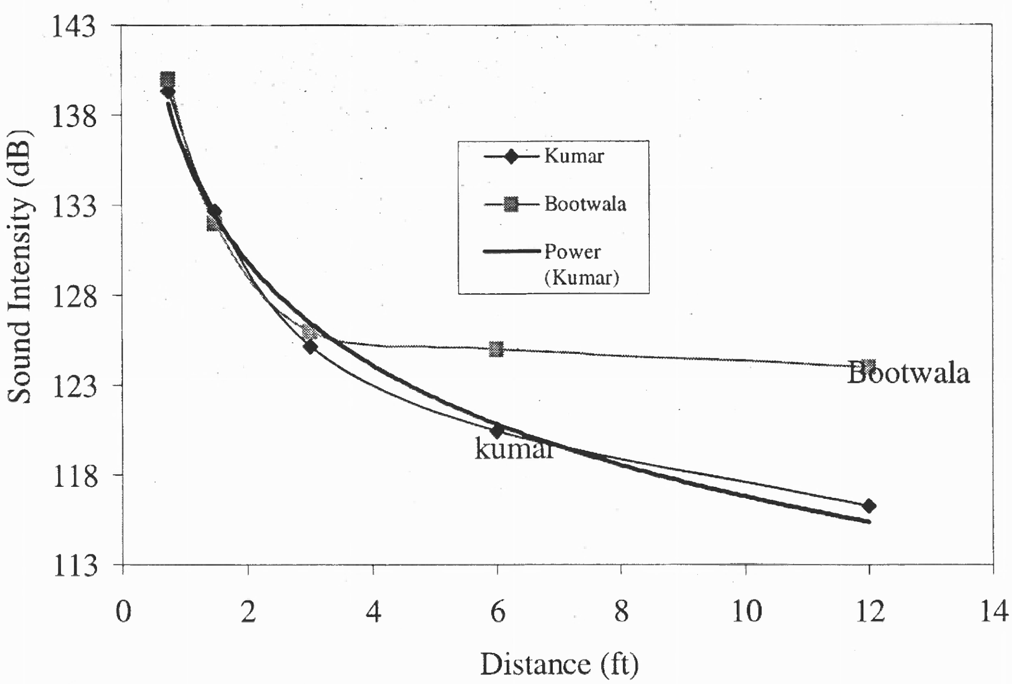


Figure A.22 Plot of Sound Intensity (dB) vs. Distance (ft) for No.5 Whistle at 6.5 SCFM Also shown Bootwala's results .

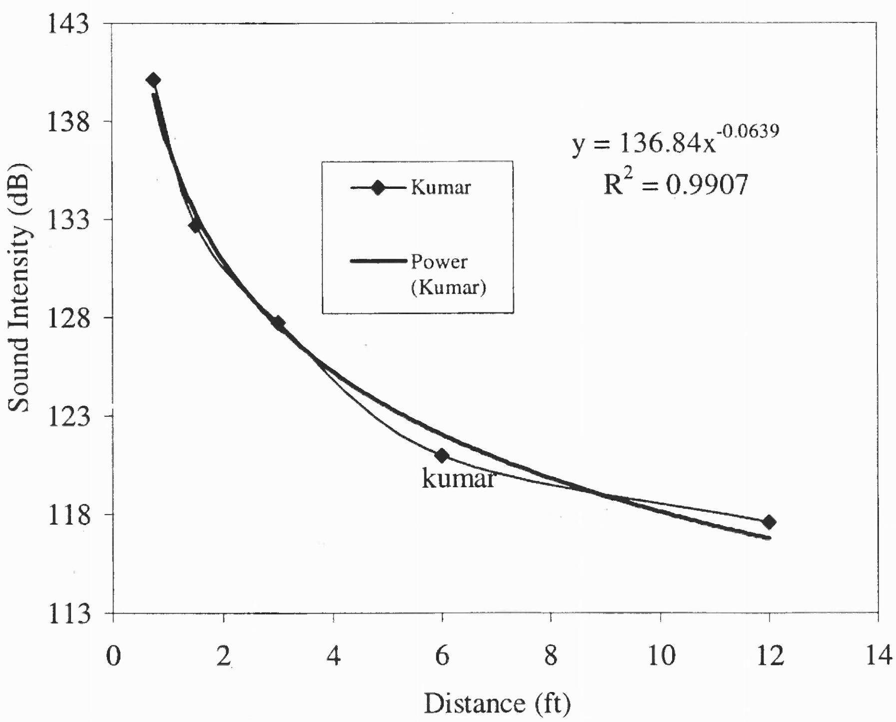


Figure A.23 Plot of Sound Intensity (dB) vs. Distance (ft) for No.5 Whistle at 7.0 SCFM

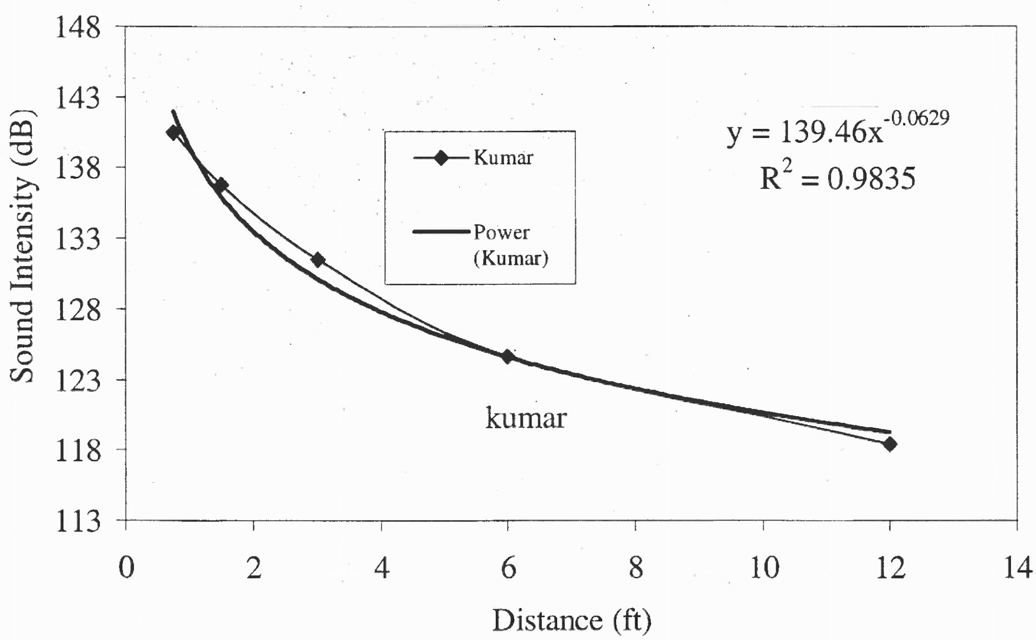


Figure A.24 Plot of Sound Intensity (dB) vs. Distance (ft) for No.5 Whistle at 7.5 SCFM

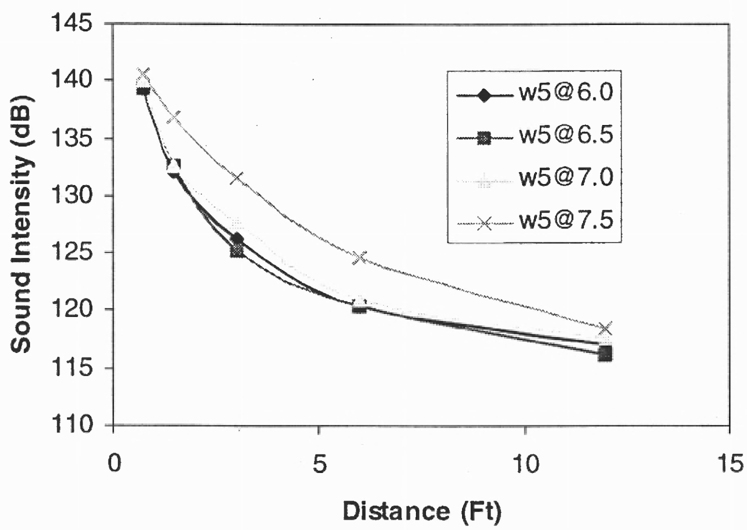
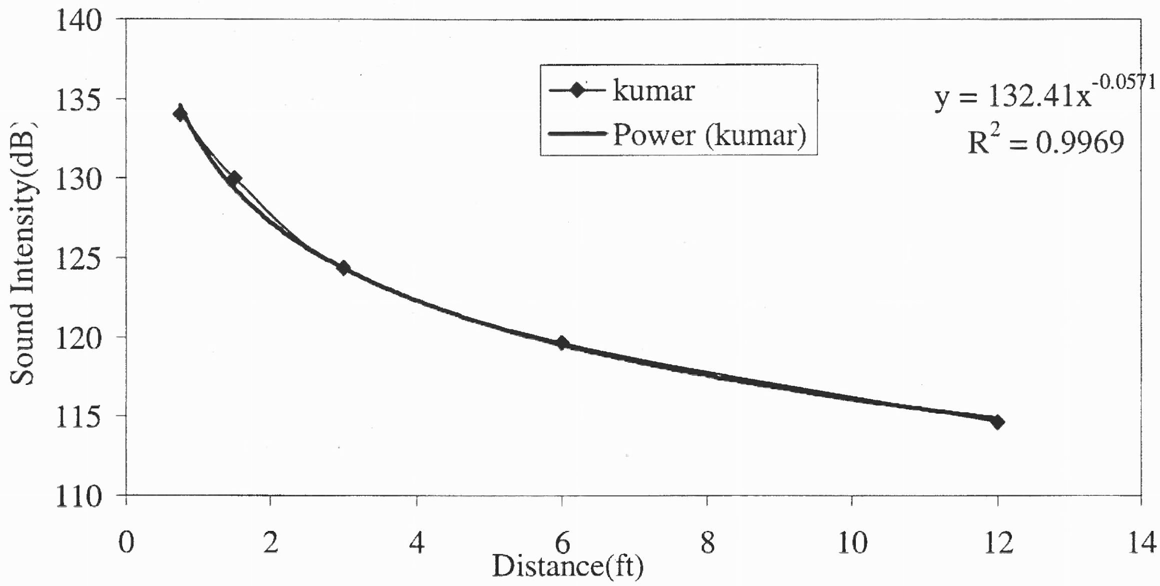
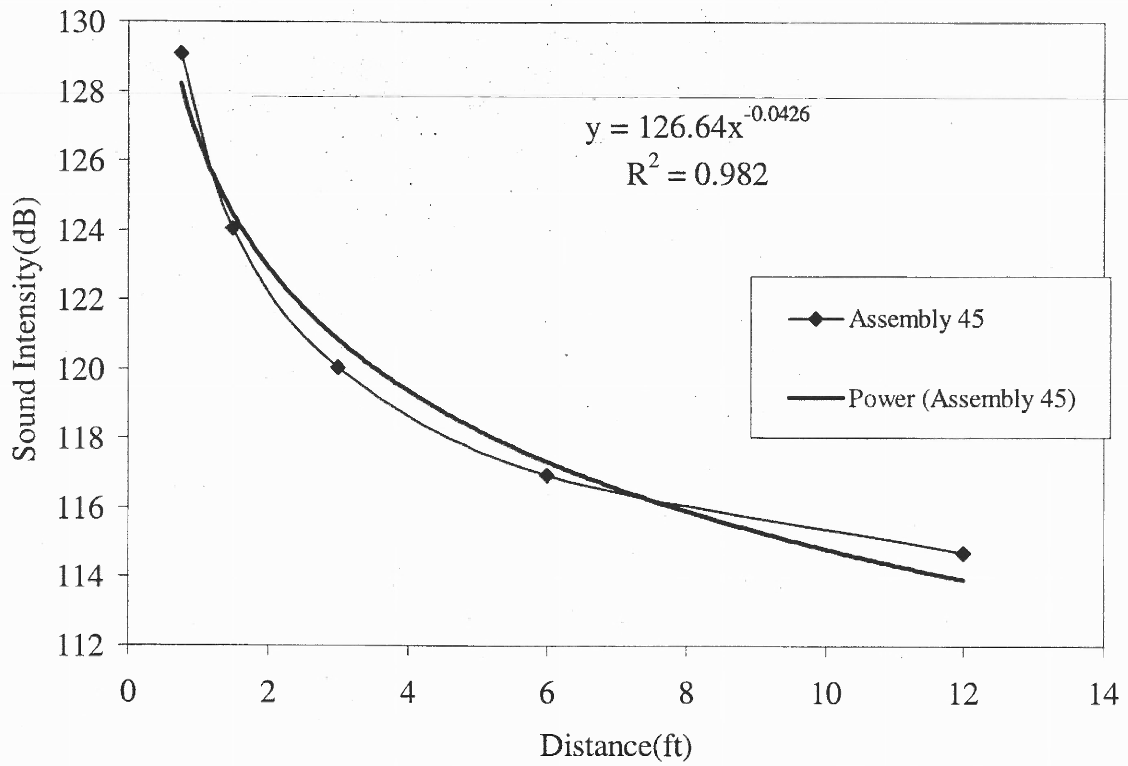


Figure A.25 Plot of Sound Intensity (dB) vs. Distance (ft) for No.5 Whistle at 6.0-7.5 SCFM all in one graph

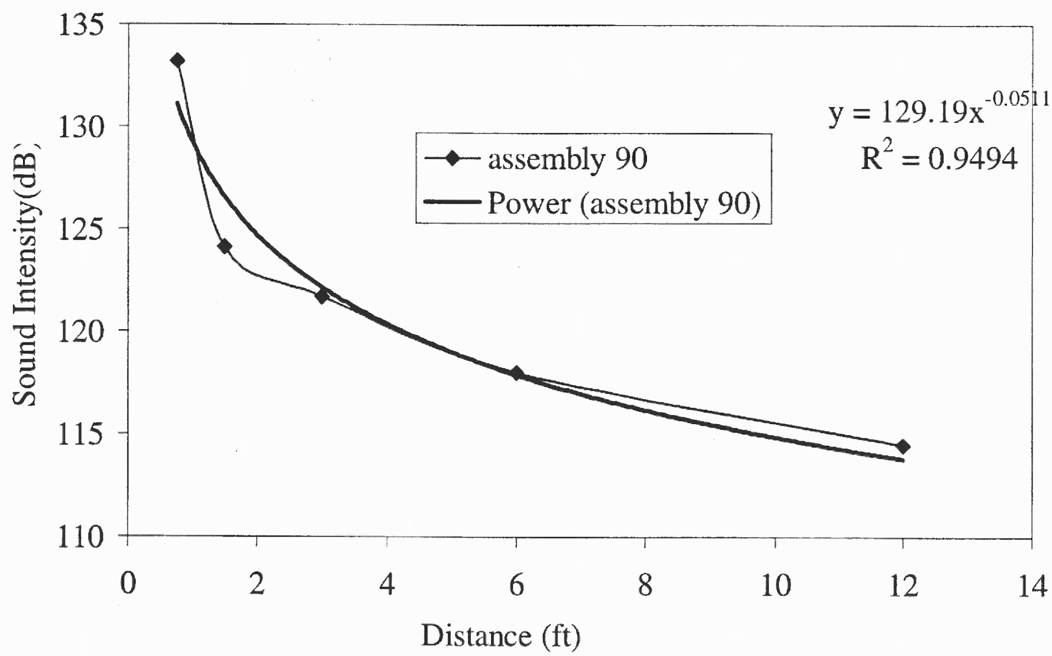
Combined Assembly Figures



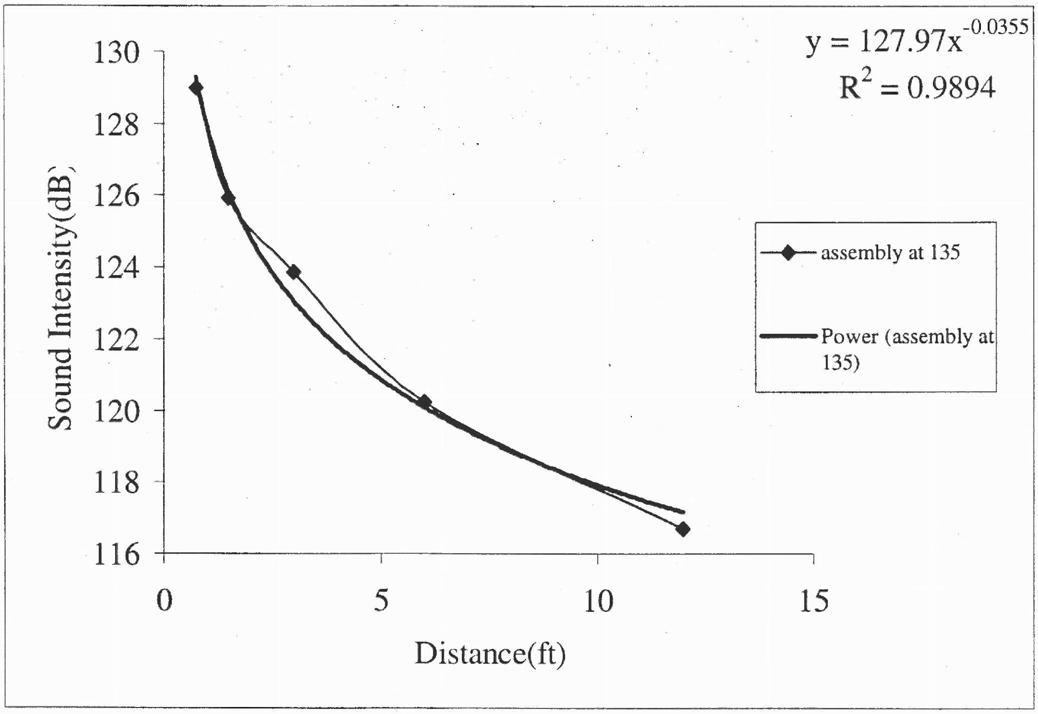
A.26 Plot for Combined Assembly at 360 or 0 degrees or at 12:00 clock time.



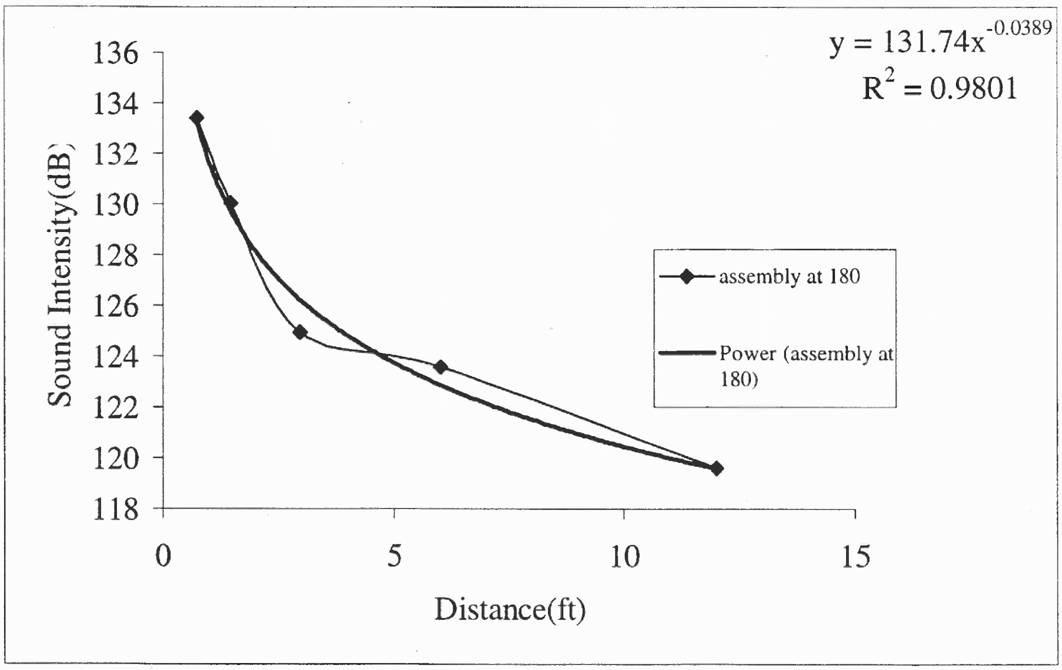
A.27 Plot for Combined Assembly at 45 degrees or at 1:30 clock time.



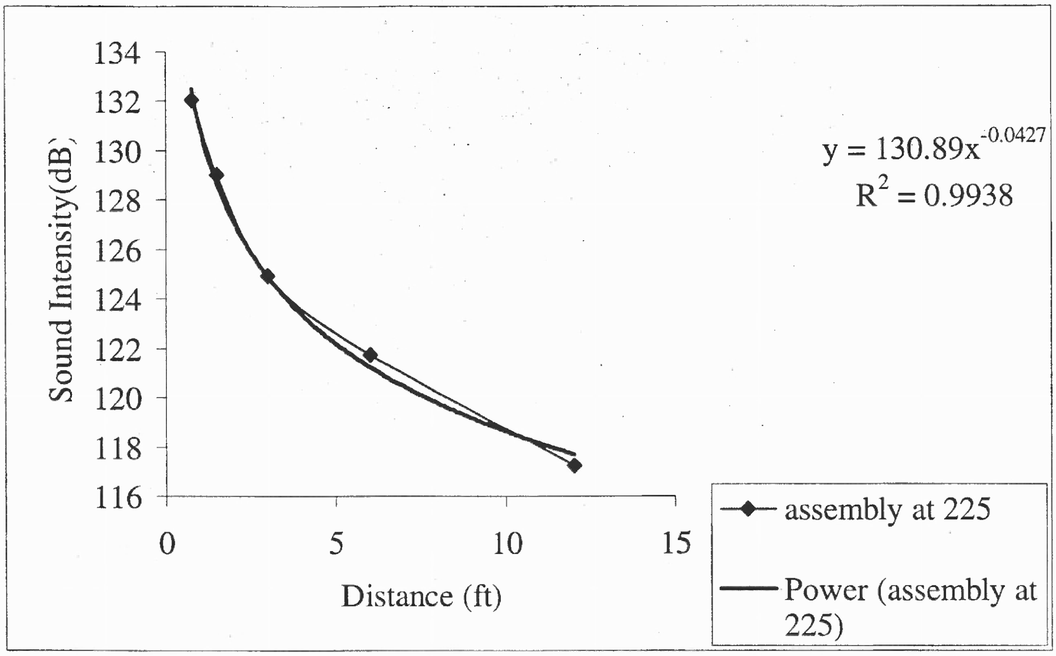
A.28 Plot for Combined Assembly at 90 degrees or at 3:00 clock time.



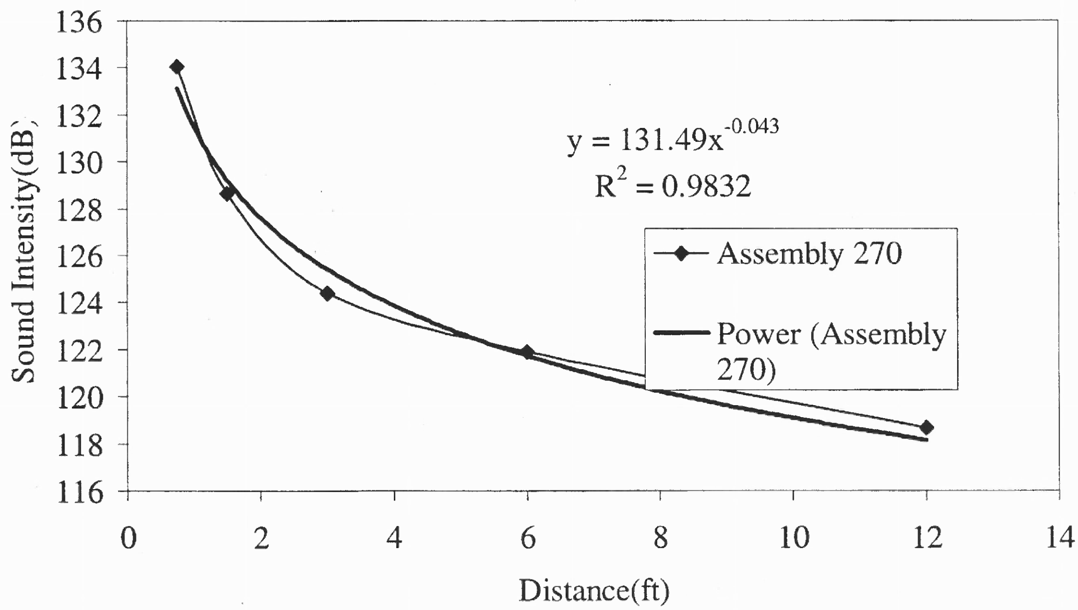
A.29 Plot for Combined Assembly at 135 degrees or at 4:30 clock time.



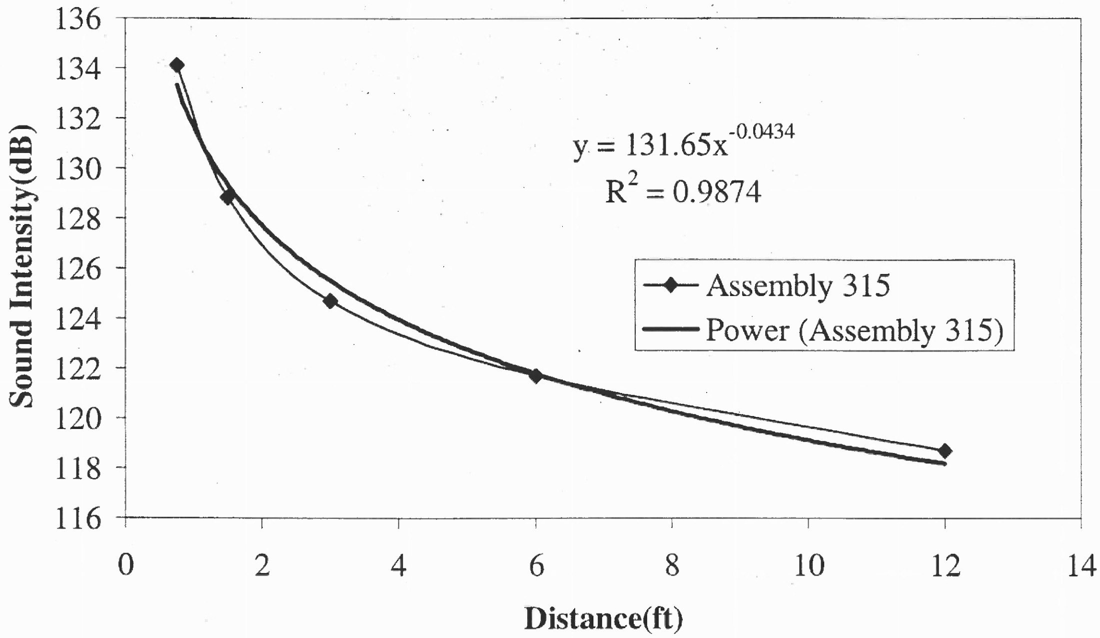
A.30 Plot for Combined Assembly at 180 degrees or at 6:00 clock time.



A.31 Plot for Combined Assembly at 225 degrees or at 7:30 clock time.



A.32 Plot for Combined Assembly at 270 degrees or at 9:00 clock time.



A.33 Plot for Combined Assembly at 315 degrees or at 10:30 clock time.

APPENDIX B

Table B.1 Showing calculated maximum intensity for combined whistle assembly at 1 inch from sonic generator.

S.no	**Position of whistle no 5 at different angels.**	**Maximum Sound Intensity(dB)**
1	45	**137.88**
2	90	**139.6**
3	135	**140.79**
4	180	**144.41**
5	225	**147.12**
6	270	**143.2**
7	315	**143.80**
8	360	**154.62**

Table B.2 Measured data for Whistle No. 1

Distance (ft)	Data at flow rate 6.5SCFM		Data at flow rate 7.0 SCFM		Data at flow rate 7.0SCFM		Data at flow rate 7.5SCFM	
	Microphone	**S.M (dB)**	**Microphoe**	**S.M (dB)**	**Microphone**	**S.M (dB)**	**Microphone**	**S.M (dB)**
12	62.52	118	59.54	118	57.54	125	51.43	132
6	58.43	114	55.6	114	53.85	120	43.8	124
3	53.45	110	51.5	110	51.31	116	38.62	120
1.5	49.33	104	48.3	106	48.66	109	35.22	115

Table B.2 Measured data for Whistle No. 2

Distance (ft)	Data at flow rate 6.0 SCFM		Data at flow rate 6.5 SCFM		Data at flow rate 7.0 SCFM		Data at flow rate 7.5 SCFM	
	Micro Phone	**S.M (dB)**	**Micro Phone**	**S.M (dB)**	**Micro phone**	**S.M (dB)**	**Micro Phone**	**S.M (dB)**
12	46.29	121	45.3	124	43.81	125	43.95	126
6	42.01	127	40.6	130	39.04	129	40.12	132
3	38.83	132	34.2	134	35.66	134	35.82	135
.5	33.99	136	30.4	136	27.37	136	25.13	136
.75	29.5	137	23.85	137	21.99	137	21.49	137

Table B.4 Measured data for Whistle No. 3

Distance **(ft)**	**Data at flow rate 6.0SCFM**		**Data at flow rate 6.5 SCFM**		**Data at flow rate 7.0SCFM**		**Data at flow rate 7.5SCFM**	
	Microphone	**S.M (dB)**	**Microphone**	**S.M (dB)**	**Micro phone**	**S.M (dB)**	**Micro Phone**	**S.M (dB)**
12	45.56	121	44.22	124	44.51	123	44.34	121
6	42	124	41.6	130	40.9	129	40.8	128
3	36.63	129	36.57	134	35	134	35.43	135
1.5	31.84	134	30.04	136	30.4	137	30.5	136
.75	26.14	137	23.5	137	24.6	137	25.64	137

Table B.5 Measured data for Whistle No. 4

Distance (ft)	Data at flow rate 6.0SCFM		Data at flow rate 6.5 SCFM		Data at flow rate 7.0SCFM		Data at flow rate 7.5SCFM	
	Microphone	S.M (dB)	Microphone	S.M (dB)	Micro phone	S.M (dB)	Micro Phone	S.M (dB)
12	45.56	121	44.22	124	44.51	123	44.34	121
6	42	124	41.6	130	40.9	129	40.8	128
3	36.63	129	36.57	134	35	134	35.43	135
1.5	31.84	134	30.04	136	30.4	137	30.5	136
.75	26.14	137	23.5	137	24.6	137	25.64	137

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